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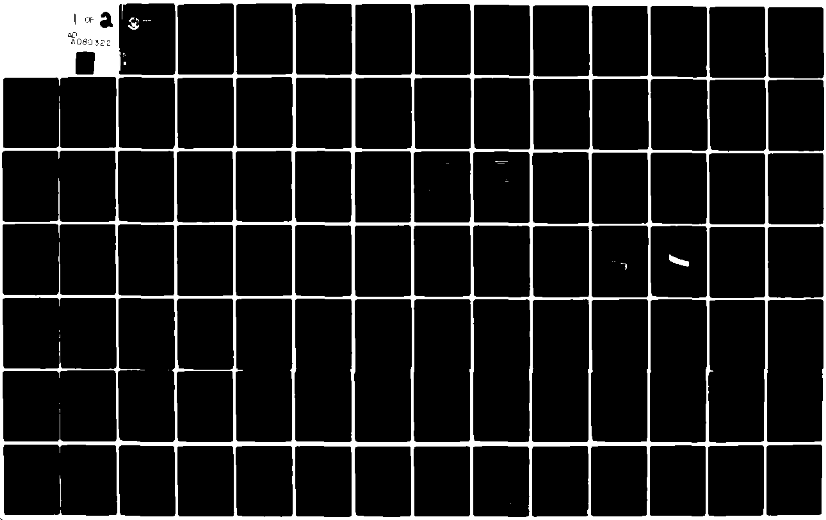

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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

[illegible] SOLID WASTE AND
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An Investigation Conducted by
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The 1976 Resource Conservation and Recovery Act encourages the recovery of material and waste derived fuels to the maximum extent practicable at federal facilities, while complying with all state and local requirements as well. The Navy's Solid Waste research project is designed to identify and develop cost effective alternatives for meeting RCRA requirements. To meet

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20. Abstract (cont'd)

this objective an immediate need of the project was to quantify and characterize the recoverable material contained in the Navy waste stream and to compile information on how these material are handled at typical Navy installations. The work was concentrated in two areas: compiling and analyzing available data about Navy solid waste composition and generation, and developing a set of realistic descriptions of typical Navy solid waste handling practices.

For waste composition and generator rate, data available from the NACWIS data base, including R^4 surveys conducted under the direction of the Naval Environmental Support Office (NESO), were compiled and analyzed. Navy facilities were listed in classes according to the amount of waste.

A simplified technique was examined for estimating quantities of the various recoverable resources generated by a Navy installation. This technique was tested against data obtained from the R^4 surveys mentioned above. The test was aimed at evaluating this relatively low-cost technique for possible use in augmenting Navy solid waste data to enable adequate field planning, selection, and preliminary sizing of Navy resource recovery systems. The technique requires a series of field observations of the volumes of waste generated and the waste's origin to estimate weight and composition. Once the bulk densities are thus derived, a few periodic volume observations will establish trends and cycles.

Existing information concerning current Navy practices for handling its solid waste was also derived from R^4 survey results obtained by the Navy. The information includes an indication of the type of personnel involved in the collection, the type of disposal methods used, useful life of landfill sites; and whether the landfill is on Navy property. The format in which the data are compiled was intended to enable the establishment of classes for collection and disposal methods and the indication of the number of Naval installations in each class.

This report also includes a brief analysis of how Navy and all other landfills will be affected by RCRA and the Safe Drinking Water Act (SDWA).

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I SUMMARY

Opportunities to recover resources from solid waste at Naval installations have been analyzed in a research project that SRI International (SRI) conducted for the U.S. Navy Civil Engineering Laboratory. SRI's research under this project is reported here; it addresses concepts of recovering energy from solid waste by utilizing naval facility energy conversion systems (i.e., its steam plants) as principal building blocks of candidate solid waste/resource recovery systems at Navy installations.

The Navy's steam plants were first characterized in terms relevant to firing or cofiring of waste derived fuels (WDF); they were then assigned to categories suitable for subsequent treatment as optional components in cost and effectiveness analyses of solid waste/resource recovery systems.

For this study, the steam plants and their boilers were classified in a simple, eight-class scheme. Size (designed heat input capacity, 10^6 Btu/hr) and type of primary fuel are the basic parameters of the classes. Four size classes and two types of primary fuel burning capabilities (coal, noncoal) were selected, and distributions of plants planned for 1985 were plotted for each of the eight classes.*

To relate the steam plants' capabilities to burning WDF, four alternative means for utilizing WDF--adding incinerators, replacing boilers, modifying existing boilers, and making hybrid conversions--were considered for each class. Incineration and modification of existing boilers were emphasized. These alternatives appeared to be the most feasible ones for near-term implementation and were therefore central to the Navy's current

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*Fuel type capability classes other than "coal" and "noncoal" may be more useful. Suggestions made after this report was completed include "coal," "noncoal," and "noncoal but readily convertible" or "solid fuel capable" and "other" as classes. These classifications are being investigated in follow-on work.

interests. Problems encountered, system modifications required, and costs associated with the alternatives in the classes were defined as clearly as the accuracy of the available data would allow.

The major conclusions of this portion of the project are:

- Although it is technically feasible to adapt Navy energy conversion systems to fire WDF in one or more of its forms, the optimal form selected should be a site-specific total system.
- Near- to intermediate-term programs should probably continue to give first consideration to waterwall incinerators and to the cofiring of solid WDF in coal-capable plants because these options are the ones most completely developed and documented.
- Package incinerators and conversion of oil burning plants to fire a fluff form of solid waste fuel may be the options with the greatest potential for the intermediate term because waterwalls would be uneconomical in many small plants and because the majority of medium-sized oil-burning plants will not be converted to burn coal.
- Pyrolytic processes to produce gaseous and liquid fuels have not been sufficiently developed as yet to be specified for commercial operation. However, these forms of WDF have widespread potential applicability. If they (liquids in particular) become available, they could become the most cost-effective alternatives; using them would minimize the necessary modifications of existing energy conversion systems. Probably 5 years or more of development and testing will be needed before the future of pyrolysis is clear.

This volume also offers suggestions for the RDT&E cited below to develop data related to specific problems that were identified during the research:

- A review of Navy solid waste components that could emit significant quantities of noncriteria air pollutants during combustion
- A preliminary technical/economic evaluation of a fluidized bed combustor preceded only by a trommel and shredder for solid waste combustion at Naval installations (perhaps a part of the DOD/DOE Great Lakes Training Station experiment)
- A study of the operating characteristics, performance, and investment and operating costs for particulate control devices for small solid waste combustion units (20 to 200 ton/day)
- A study of the costs of controlling nuisance odor problems at resource recovery plants by scrubbing building ventilation system exhaust

- A study of possible design improvements for shop-fabricated incinerators to achieve more complete combustion of fixed carbon in ash and to achieve better process control
- A continuing review and evaluation of developments in small-scale solid waste conversion units. (Auger bed incinerator development is a possible subject to be included, as are updates on gasification and pyrolysis units. Identifying European developments that employ mechanical grate units is another possible topic.)
- A preliminary technical/economic evaluation of the O'Connor rotary combustor.

The Navy is likely to encounter these issues in implementing resource recovery from solid waste.

II INTRODUCTION

A. The Problem

Operating costs at Naval shore activities have increased dramatically since 1973, largely because the cost of imported petroleum has quadrupled. In FY 1973, Naval shore activity energy costs were approximately \$173 million;* estimated FY 1978 energy costs at the same activities were approximately \$500 million, despite a 20% reduction in energy use by the activities during the same 5-year period. The need to halt and, if possible, reverse the cost trend in the energy bill is obvious. Consequently, the Navy is studying a number of options that may help reduce energy costs at its shore activities. One option involves purchasing and substituting low-cost (possibly less than $\$1.00/10^6$ Btu) waste derived fuels (WDF) for significantly higher cost primary fuels (i.e., oil, gas, coal).

Another energy-related option that may help reduce shore activity operating costs is Navy recovery of fuels from its own solid wastes. If the credits for the WDF produced and for reduction in the disposal (landfill) costs outweigh the costs of producing the WDF and modifying the existing systems to burn the WDF, this option can be quite attractive. However, the break-even costs in this second option for producing WDF may be critically sensitive to landfill cost projections and to other site-specific factors such as the costs of air and water pollution abatement measures.

At present, deciding how and where the implementation of either or both of these options might be cost-effective is both difficult and risky. In only a few instances has implementing either of the options proved to be cost-effective. Furthermore, neither the successes nor the failures

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*Navy Energy R&D Plan, Vol. II (1977).

have been sufficiently analyzed in technical and economic terms. This is particularly true of operational and maintenance (O&M) factors for small- to medium-scale systems, the sizes appropriate for most Navy shore activities.

A significant number of feasibility studies* have been performed by numerous engineering firms for U.S. municipalities and large utilities to evaluate the potential for processing municipal solid wastes into WDF and for utilizing the fuels under specified large-scale conditions. These studies routinely use estimates of full-scale operational data extrapolated from pilot system cost and performance data. However, the accuracy of these estimates has been disappointing. To compound the problem, adequate data have been available on the pilot systems of only a few of the technically feasible alternatives, thereby limiting the number of alternatives that have been given serious consideration.

The Navy has also had similar site-specific studies performed for a number of its larger activities. Many of the studies for the Navy (using essentially the municipal system data bases) have indicated that processing an activity's solid waste into fuel and using this fuel in the activity's boiler plants would be uneconomical because the plants are small and the process is capital-intensive. On the other hand, studies of some Navy activities† have concluded that purchasing WDF and cofiring them with primary fuels would be cost-effective. In either case, typical conditions and system requirements at Navy installations that could contribute to making a particular processing technique or WDF utilization system cost-effective have not been set forth for the broad spectrum of Navy activities. Apart from rough scale-of-operation data, little or no cost or effectiveness sensitivity information is available to guide system designers or decision makers.

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*SRI project staff members have reviewed more than 30 such reports (see Chapter VII, Bibliography).

†Charleston Naval Shipyard and Philadelphia Naval Shipyard, for example.

The objective of the work reported here, therefore, is to assemble available energy conversion system/WDF utilization data, analyze them for relevance to Navy applications, and portray the results in terms suited to subsequent analyses of total solid waste/resource recovery systems. Incineration technology and cofiring of WDF with primary fuels in conventional boilers are covered in detail. The processing of solid wastes into WDF is summarized to the extent necessary to describe technical feasibility and to estimate costs of processing Navy solid wastes into WDF of various kinds.

B. Previous Related Work and Data Sources

SRI had previously examined ways of estimating the potential for utilizing WDF in Navy boiler plants at a few selected sites in two brief studies. Understanding gained during these studies, particularly of the difficulties in obtaining realistic estimates of costs and performance of small-scale systems, helped to focus the work reported here. With this orientation, SRI's project team abstracted data from available solid waste/resource recovery feasibility studies.

C. Scope of This Volume and Its Relationship to the Total Project

This volume reports work on:

- Characterizing Navy energy conversion systems
- Developing a classification method to indicate the potential for utilization of WDF of each class
- Estimating the number of systems in each class
- Assessing the potential for converting systems in each class to use alternative forms of WDF
- Identifying modifications required and technical and logistic problems anticipated, and estimating costs of implementing WDF fuel alternatives for each class.

Typical Navy energy conversion systems (boiler plants) and their operating characteristics are surveyed, and the technical potential of these plants for using WDF in several forms is assessed. Within the limitations of data availability, the findings reported here are

representative of technically feasible energy conversion components (the WDF utilization subsystem) of total solid waste/resource recovery systems that the Navy could consider implementing in the next 5 years.

Two special studies were performed as part of the effort covered herein. The first, "Mass Burning of Refuse in Shop Fabricated Incinerators," was performed by SRI staff members, with contributions from project consultants, and is included as an appendix to this report. The second, "Waste Fuels Utilization in Existing U.S. Naval Base Boilers," was performed by Gilbert/Commonwealth under subcontract to SRI and is reported separately.

These special studies concern two of the most important near-term options--installation of package incinerators and modification of existing boiler plants. Information from these special studies is discussed in Chapters IV and V of this volume.

III CHARACTERIZATION OF NAVY SHORE ACTIVITY ENERGY CONVERSION SYSTEMS AND DEVELOPMENT OF A CLASSIFICATION METHOD

In prior research* under other Navy solid waste contracts, SRI's first characterizations of the boilers and boiler plants operating at the Navy's facilities were only partially completed. General information about the boilers (e.g., size, activity and building locations, fuel types, average fuel throughput, boiler types, and manufacturers) was obtained for approximately 2,000 Navy boilers. Site-specific features to be considered in analyzing the technical and economic feasibility of co-firing WDF were also identified. Information of this kind, available to SRI's study team at the outset of this project, provided a good background for completing the task of characterizing Navy energy conversion systems and for developing a classification scheme suited to evaluating "typical" Navy energy conversion plants as components of solid waste/resource recovery systems. The approach used to characterize Navy boilers in this study is described below, followed by an explanation of how a classification method to facilitate analysis was developed.

A. General Characteristics

1. Size

A primary characteristic of Navy boilers and boiler plants that must be accounted for in a classification scheme are their sizes in terms of heat input capacities or steam output capabilities. Many other features, such as use, type, pollution control requirements, and possible modifications, correlate roughly with size. The obvious reason for assigning

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*SRI International, "A Pilot Study of the Potential for Navy Utilization of Solid Waste-Derived Fuels," Contract N00014-76-C-0351 (June 1978) and "Potential of Waste-Derived Fuels to Offset Fossil Fuel Consumption at Selected Naval Facilities," Contract N62583/78-M-R222, Technical Memorandum (April 1978).

such importance to size is that boiler technology for large and small boilers has advanced along different lines. Of course, no absolute generalizations based on size can be made. In general, however, boilers with heat input capacity of 100×10^6 Btu/hr or greater are usually custom-designed, field-erected units. By contrast, those with capacities of less than 20×10^6 Btu/hr are more than likely shop-fabricated and of relatively unsophisticated design. Boilers with even smaller capacities are probably simple fire tube designs ordered from catalogs and intended for steam heating of spaces (saturated steam) rather than for generating process quality steam (i.e., high-pressure, superheated steam).

The Navy's major boiler plants (i.e., the boilers and all of their support equipment at large activities) are usually designed around multiple boilers of common or similar design and size to facilitate O&M. Total boiler capacity of these plants is usually high enough that the peak expected steam load can be produced by about half the boilers operating at full design capacity. As a rule, significant amounts of excess boiler capacity are found at plants where the process steam load is high and steady, and where cogeneration is practiced.

Activities requiring large steam plants often have central steam distribution systems, obviating multiple small or medium boilers distributed throughout the activity. Shipyards and air stations typically have installations of this type. On the other hand, activities with little or no demand for process heat (e.g., training stations) are likely to have many smaller boilers, each serving a barracks, a classroom, a galley, and so on.

The size (input in 10^6 Btu/hr) distribution of Navy boilers is shown in Figure 1.

2. Fuel Type

Another characteristic certain to be important in a classification scheme for boilers and boiler plants is the type or types of fuels they can burn. Fuel type is important for many reasons. The designs of the fire box, the heat exchanger, and all the auxiliaries of the boiler take

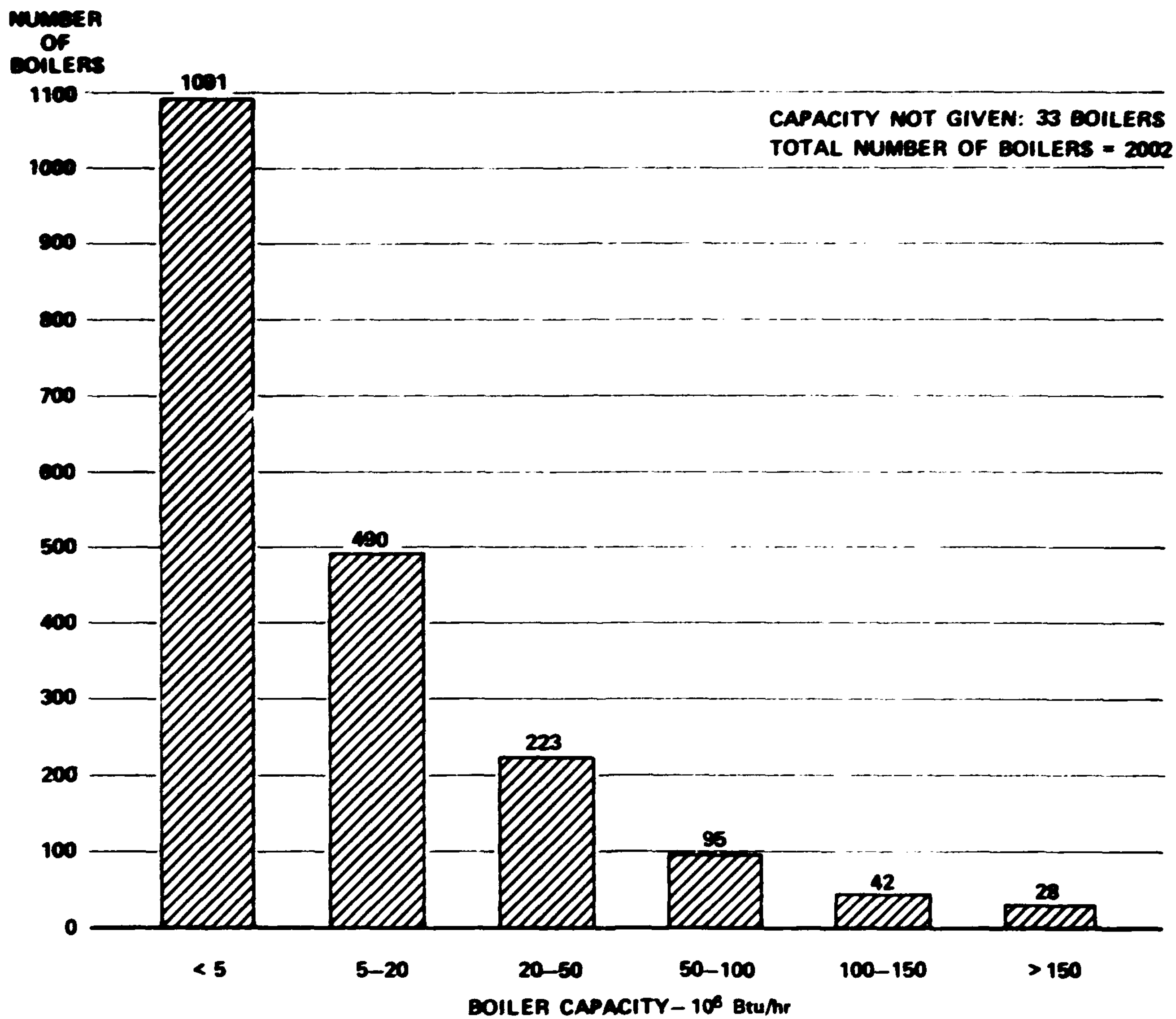

FIGURE 1. NUMBER OF BOILERS BY BOILER CAPACITY

fuel characteristics into consideration. The physical and chemical nature of the fuel will determine the handling requirements, as well as the burning and clean-up requirements. In fact, the efficiency (thermodynamic and economic) of a boiler is very much a function of how well the design of the boiler and its fuel are matched. (The Gilbert/Commonwealth report provides a detailed account of the importance of boiler and fuel compatibility.)

The types of fuels currently used by Navy shore facilities as primary fuels can be generally classified by their physical state as solids, liquids, or gases. Numerous fuels in each of these three states are available to the Navy (e.g., solid fuels include coals, woods, and peat; liquid fuels include petroleum distillates and residuals; gases include natural gas, LPG, and propane). Each has somewhat different physical, chemical, or burning characteristics. Theoretically, optimum performance is achieved when the characteristics of a single specific fuel determine the design of a plant. In practice, however, a plant must be able to accommodate variations in the fuel. This is particularly true of Navy plants, which must meet the requirements of the Navy for operational flexibility.

Older, large Navy boilers were usually designed to burn coal. However, these coal-fired plants have almost universally been modified to burn oil and/or gas and can no longer burn coal. Some of them will be converted, with various degrees of difficulty and at significant cost, back to coal. Plants originally designed to burn only oil or only gas can, without major difficulty, usually be modified to burn either fuel interchangeably, and all the larger Navy boilers have been so modified. Unfortunately, plants originally designed to fire oil or gas are not so readily modified to burn coal or other solid fuels.

To examine the role that the "type of fuel" characteristic might play in classifying Navy boilers, we first examined the distribution of these boilers by the type of fuel being burned at present (see Figure 2). Oil-burning boilers dominate. We knew, however, of plans and directives that would change these distributions (e.g., Navy plans to reconvert a

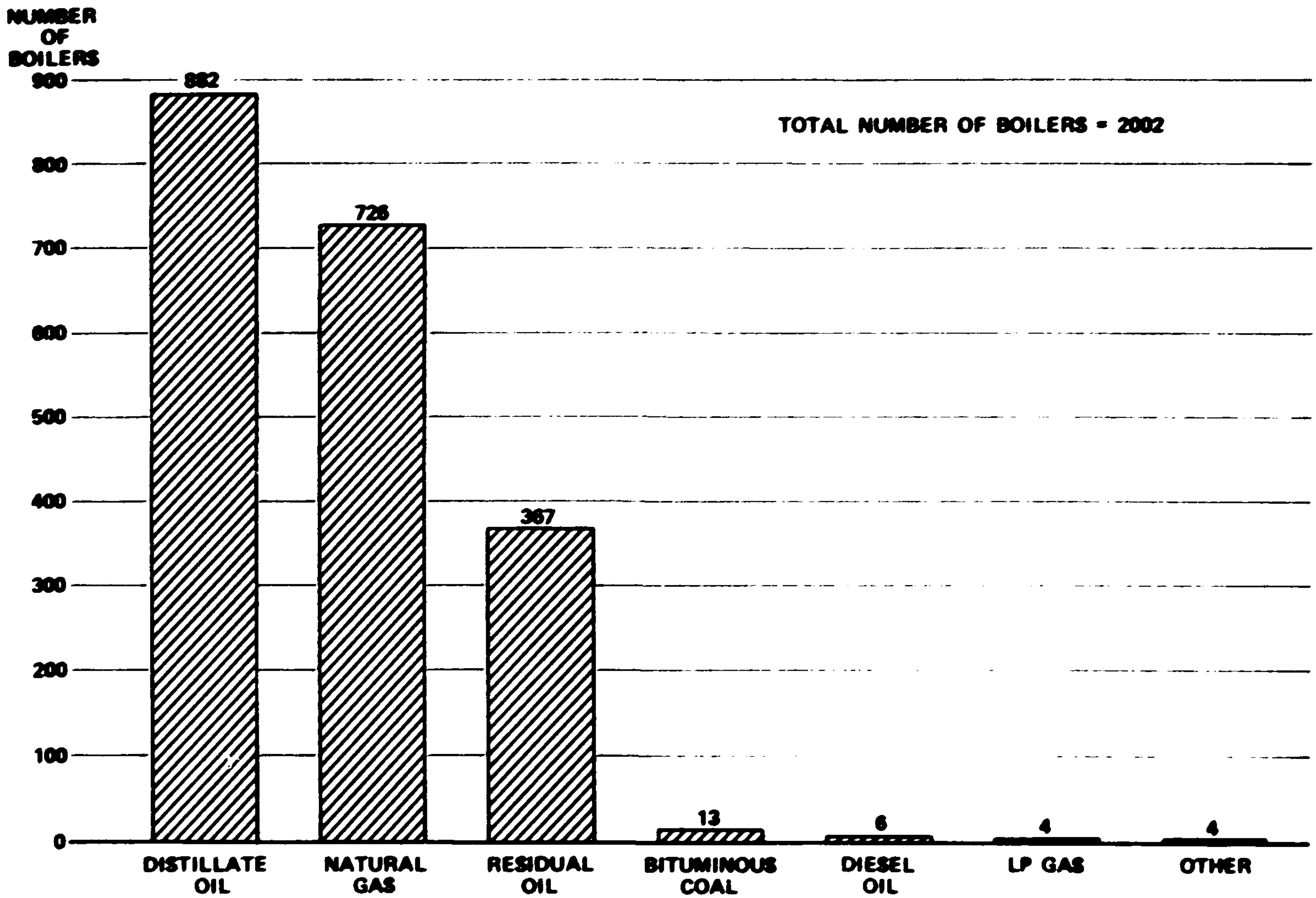

FIGURE 2. NUMBER OF BOILERS BY FUEL TYPE

significant number of its previous coal boilers back to coal and OSD directives that require all newly constructed boilers 100 x 10^6 Btu/hr or larger to be coal-capable). The effects of converting the 20 plants given in Table 1 on the distributions of Figure 2 are shown in Figure 3. Although these boilers are few, their size and the relative versatility of coal-capable plants for burning a variety of fuels without major modifications make them important. In fact, coal-burning capability may be of such importance that characterizing Navy plants as "coal" or "non-coal" might suit our purpose. A two-category representation of fuel type, combined with three or four size categories and perhaps categories based on a few other boiler plant characteristics might be adequate.

3. Fuel Throughput

In our earlier work, it appeared that the quantity of fuel of a given heat value fired in a given time (e.g., lb/hr) to meet the steam demand and also the heat release rate (e.g., 10^6 Btu per lb/min) needed to meet a varying demand could importantly influence the form, as well as the amount, of WDF a plant could utilize. In other words, because the heat content of the primary fuel, its volatility, and the way in which it will be introduced into the furnace were all taken into account in designing the boiler, these same features of the cofired fuels should be important in determining WDF cofiring capability. Fuels with radically different characteristics would have different limits in the rates (minimum as well as maximum) at which they could be properly consumed in a plant of a given design, and they would adapt differently to fluctuating demands. (The relationship between primary and secondary fuel heating values, rates of firing, and matching of boiler characteristics is discussed in some detail in the Gilbert/Commonwealth report.)

Whether the typical amounts of fuel throughput, as a characteristic, would need to be included in the classification was unclear. We had observed in our earlier studies that the total annual throughput and the design capacity of a normally operated boiler could be related with a simple function, at least as a first approximation. But if throughput was to be indicated on a quarterly, monthly, daily, or hourly basis (as

Table 1

NAVY COAL BURNING CAPABILITIES AND CONVERSIONS: FY 1974-1985

Burning Coal at Present (1978)
- MCB Camp Lejeune
- NSY Charleston
- Subbase Bangor

Under Construction* (1978)
- MCAS Cherry Point
- PWC Norfolk

(Five activities above will burn coal by 1980)

Boilers in FY 80 MILCON Program

		10^6 Btu/hr	Year
1.	PWC Norfolk	865	
2.	NAB Little Creek	270	
3.	NOS Indian Head	495	1980
4.	MCEDC Quantico	301	
5.	NAS Brunswick	254	
6.	NSY Mare Island	125	
7.	PWC Great Lakes	500	
8.	NSY Norfolk	720	1981
9.	NAS Memphis	300	
10.	Newport Bldg. 86	290	
	Newport Bldg. 7	150	1982
11.	MCRD Parris Island	200	
12.	Subase New London	375	1982
13.	PWC Pensacola	250	
14.	NSY Portsmouth N. H.	360	1984
15.	NAS Jacksonville	200	
	Total	5,655	

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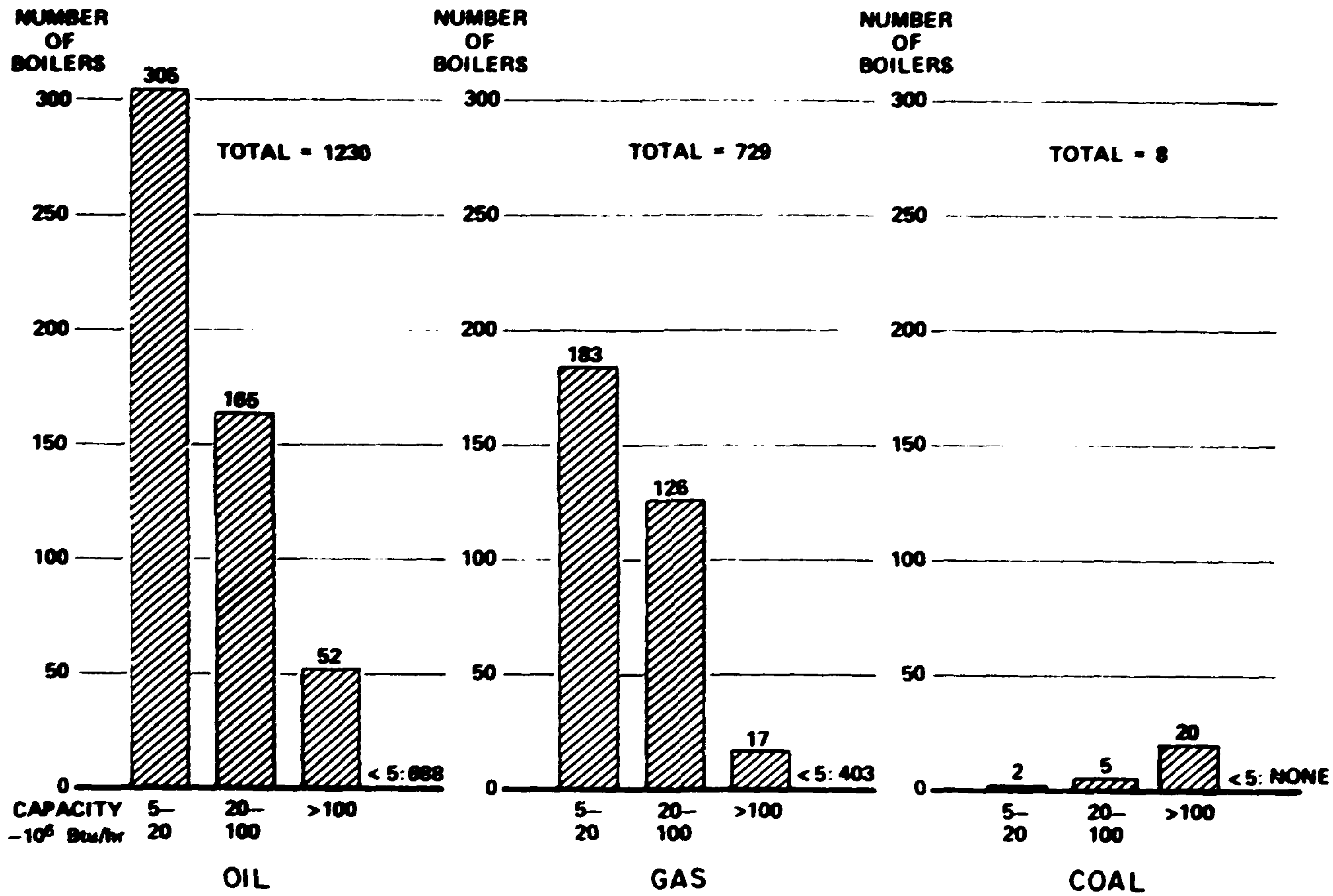
*If a boiler is to have input capacity of 100×10^6 Btu/hr (400 bbl/day) or larger, it must be constructed as a coal burner. If low-sulfur coal is not available, the unit will be constructed to fire both coal and fuel oil.

If a boiler is to be between 50×10^6 Btu/hr (200 bbl/day) and 100×10^6 Btu/hr (400 bbl/day), it is to be constructed to burn coal. If low-sulfur coal is not available, the unit can be constructed to burn fuel oil but must be convertible to coal at a later date.

Source: Information obtained from NAVFAC 102 (March 1978); DOD directives regarding new or replacement boilers.



TOTAL NUMBER OF BOILERS = 2002 (Includes 2 boilers of other type of fuel and 33 boilers of unknown capacity)

FIGURE 3 NUMBER OF BOILERS BY FUEL TYPES (1985)

might be the case for determining WDF utilization potential), relating throughput and boiler capacity became much more complicated. For example, Figure 4 (prepared from NAPSIS quarterly estimates of percentage of annual throughput) shows seasonal variations for several plants. But Figure 5 (plotted from monthly consumption data for a single large plant as reported in DEIS II records) indicates seasonal variations more strongly.

Only a few activities were examined for monthly profiles of fuel throughput similar to Figure 5 because of the excessive labor required to extract the data manually from the fuel consumption records available at SRI--hard copy computer printouts of DEIS II monthly reports by Major Claimant. (Another SRI project* for the Navy sought to facilitate the analysis of DEIS II reports of Navy energy consumption. When this computer-managed data file becomes available, a more comprehensive study of consumption versus capacity should be performed.)

We decided that, although it was undoubtedly important in calculating cofiring potential and economic data for a given plant, we would not use fuel throughput as a primary variable in our boiler classification scheme. Instead, it appeared that size (in 10^6 Btu/hr) was a reasonable substitute; if throughput were needed for this study we assumed that the following relationships would suffice:†

- Average monthly throughput ~30% of designed capacity (10^6 Btu/hr) × 720 hr.
- Peak monthly throughput ~50% of designed capacity (10^6 Btu/hr) × 720 hr.
- Maximum monthly throughput ~400% minimum monthly throughput.

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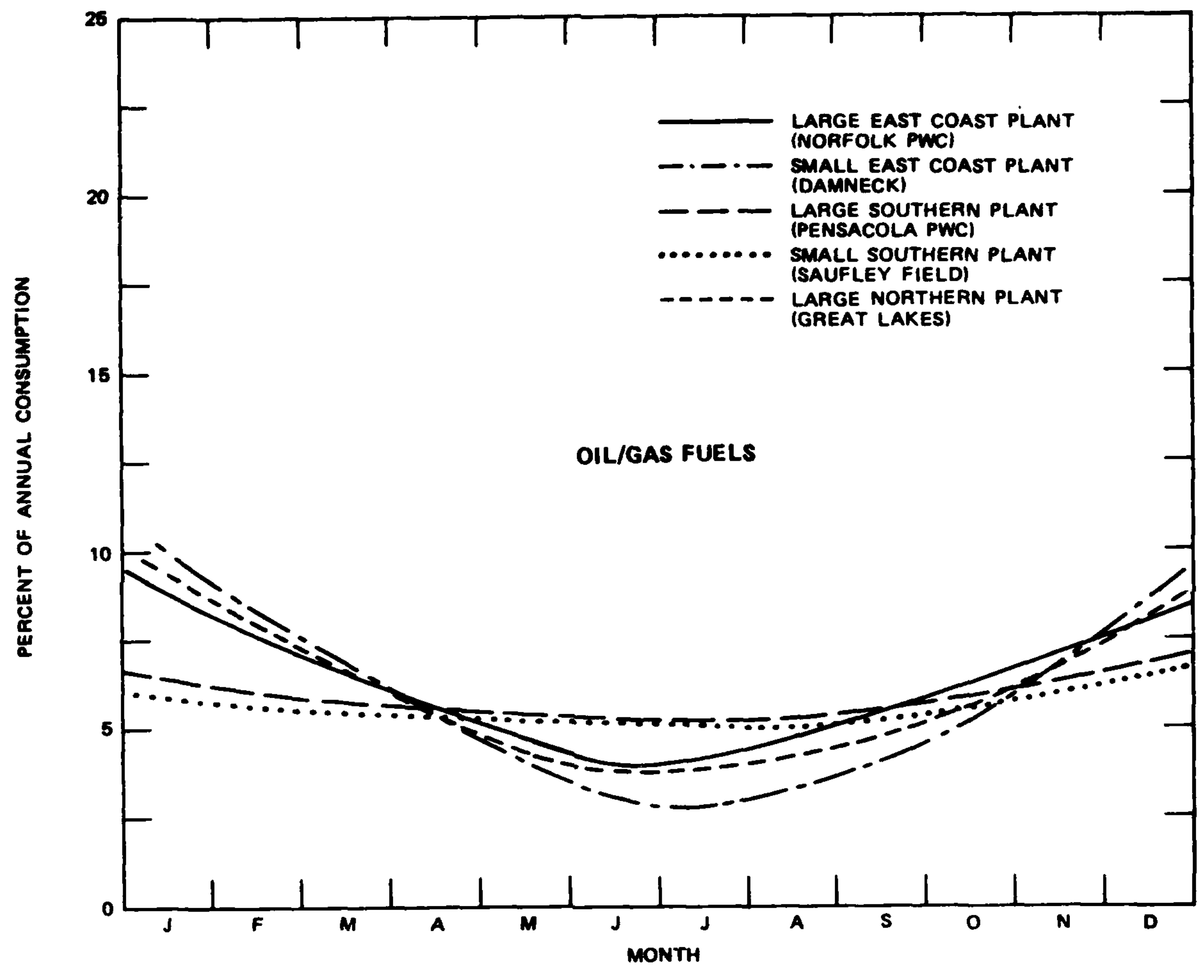
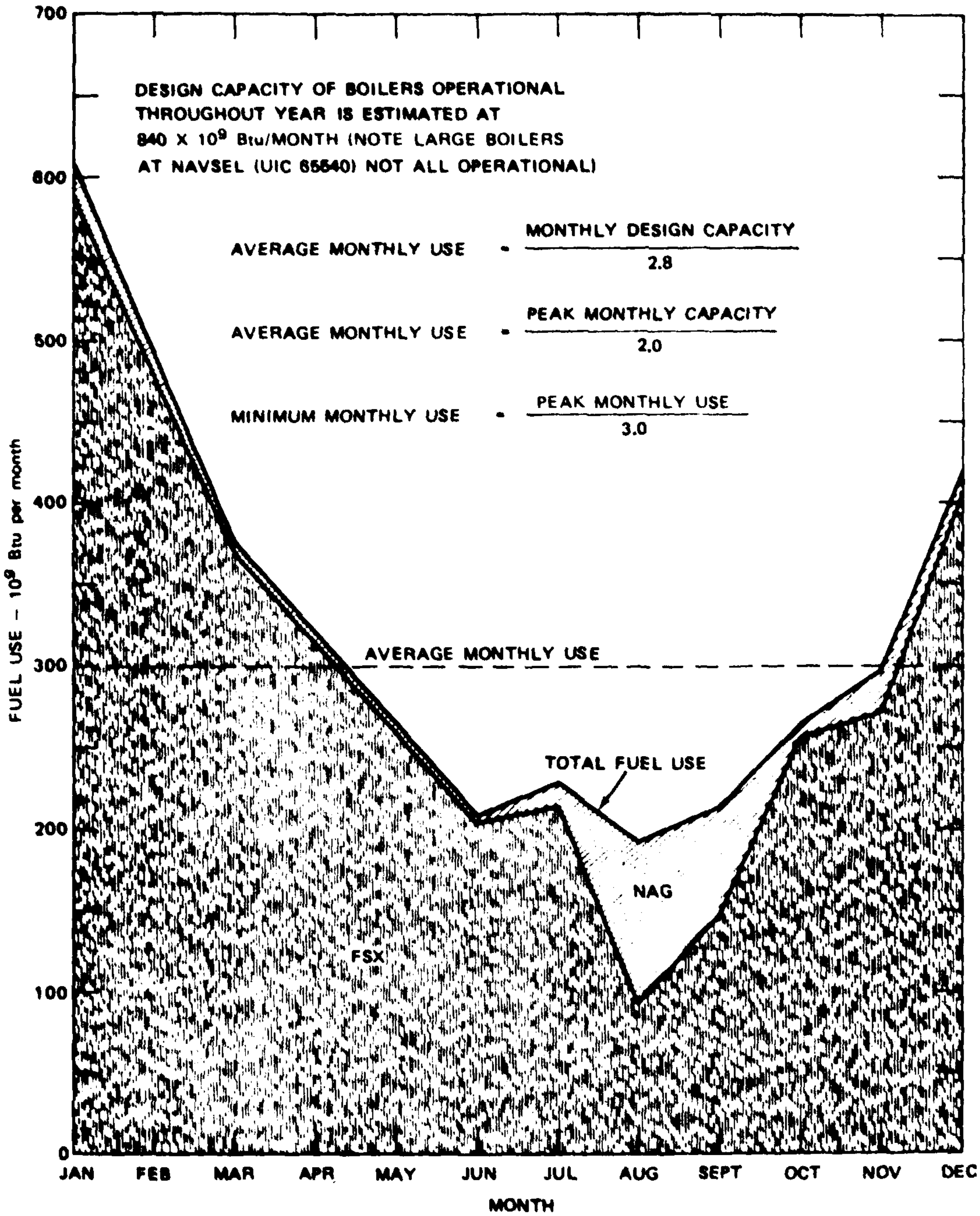
*Project NEUPAAS (Users' manual for the Navy Energy Usage Profile and Analysis System) conducted by SRI for OPNAV 413.

†The reader is cautioned that these relationships result from averaging data from a sample of five arbitrarily selected plants. The relationships should be reexamined when NEUPAAS is available.



DATA SOURCE: NAPSIS MASTER FILE 1975

FIGURE 4. SEASONAL VARIATION IN FUEL CONSUMPTION



SOURCE: DEIS II MONTHLY REPORTS 1977
NAG = NATURAL GAS
FSX = HEATING OIL

FIGURE 5. EXAMPLE OF SEASONAL VARIATION OF FUEL USE AT LARGE FACILITY (NSY–PHILA.)

4. Other Characteristics

Descriptive information characterizing Navy boilers, such as boiler age, manufacturer, type (water tube or fire tube), economizers, superheaters, and so forth was examined for possible use in the classification scheme. However, none of these items appeared to provide direct information useful in typifying Navy boilers for this study, and for the time being, we omitted this level of detail from our classification scheme. Nonetheless detailed information about Navy boilers can be obtained when needed from engineering and utility files and routine reports.

B. Site-Related Characteristics

The type of information discussed above includes those kinds that could be used to characterize the Navy boiler plants, without regard to regional or local physical site requirements. Several analyses were performed to ascertain whether Navy boilers had well-defined group characteristics in common that were related to regional conditions such as climate or indigenous fuels. Some evidence was found that small boiler plants of recent vintage varied by region of the United States (e.g., oil was preferred in the North and Northeast, gas in the South and West). Because only two coal-capable boiler plants were operational, no regional preference for them could be determined. Proximity to ample supply of a specific low-cost fuel probably influenced the choice of boiler type in earlier years. However, with pipelines, railroads, trucks, and barges conveying fuel to nearly every point in the United States, regional groupings are probably no longer so important, at least not for plants in the size range of those the Navy operates.

Local conditions can dictate a number of boiler plant design and operating factors. Of particular importance are local conditions that could prevent utilization of WDF, including space limitations, environmental restrictions, lack of a rail trunk line, or lack of feasible truck access to the boiler plant site. These problems, as well as numerous

institutional obstacles, are reported* to have resulted in the cancellation of several resource recovery/energy conservation projects. Although factors such as these can constrain or eliminate options that might otherwise be feasible, in this broad characterization of boilers and boiler plants we found no adequate way of accounting for uniquely local factors as they related to boiler plants as "types." We therefore omitted local influences from our classification scheme. These factors will, however, have to be taken into account in the final stages of the analyses.

C. Development of a Classification Method for Navy Energy Conversion Systems

The characterization effort was the first step in sorting out information from detailed day-by-day records on individual boilers to categorize attributes of the Navy's energy conversion system. It was then necessary to select those characteristics that most effectively (and efficiently, insofar as data management is concerned) represent the technical and economic features of these energy conversion elements in the analyses of solid waste/resource recovery systems. To make these selections, we needed to know, at least roughly, which characteristics had to be studied directly, which could be represented by other attributes of the total system, and which could be omitted. The procedure used to select the characteristics included in the classification scheme is discussed below.

We first developed an overall systems analysis structure (see Figure 6) to indicate conceptually what information should result from our analysis. From this structure, it became apparent that the analysis should seek to compare different types of existing total solid waste systems with technically feasible alternative solid waste/resource recovery systems--in particular alternatives that provide for energy recovery.

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*Gordian Associates, Inc., "Overcoming Institutional Barriers to Solid Waste Utilization as an Energy Source," Final Report prepared for U.S. Department of Energy (November 1977).

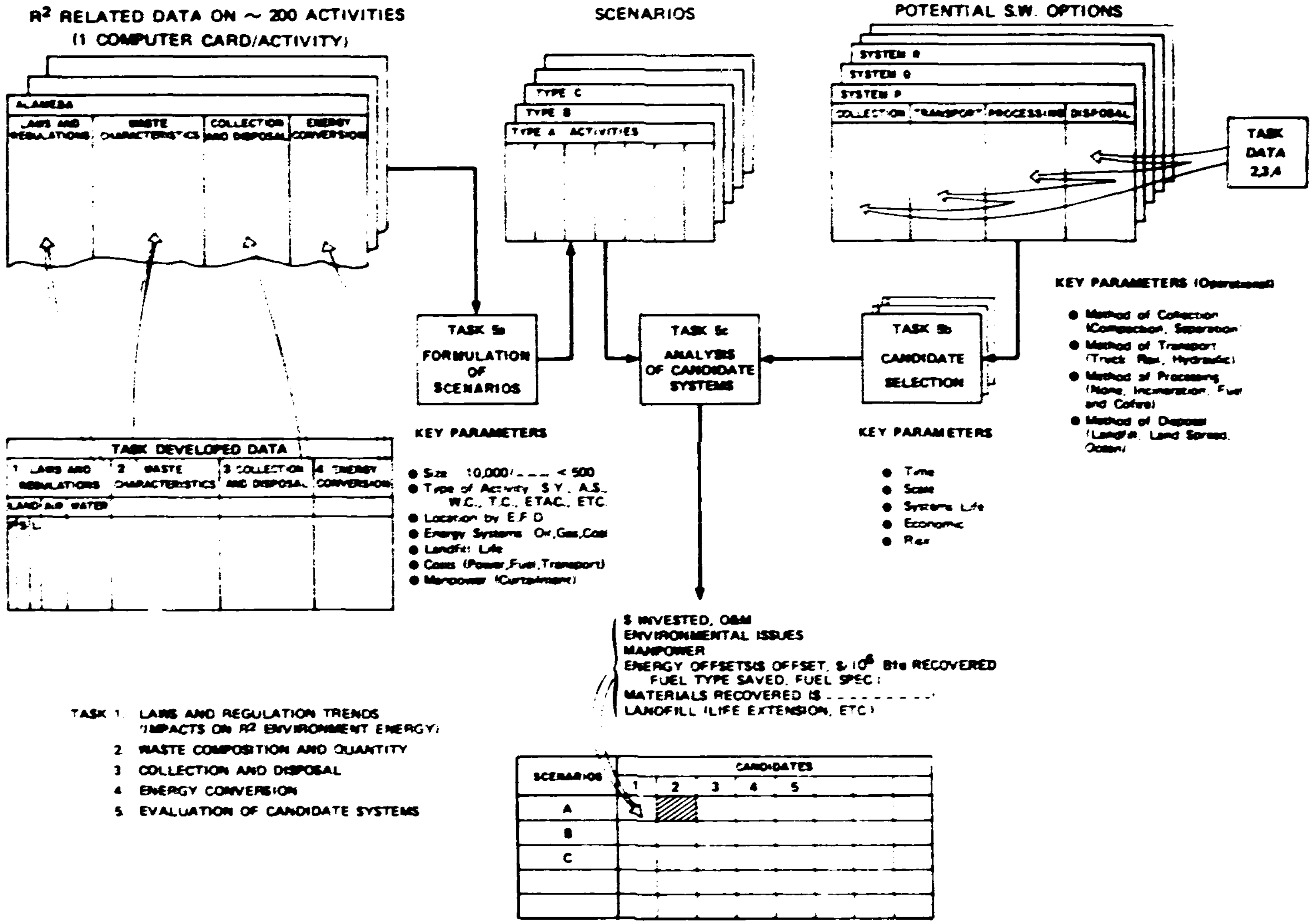

FIGURE 6. STRUCTURE OF SYSTEMS ANALYSIS FOR PROJECT

The main yardsticks chosen for the comparisons were economics, environmental aspects, and manpower.

For classification purposes, the key words were "different types of existing systems" and "alternative systems." We knew that the Navy's existing energy conversion systems would all be different if enough details were considered. From previous studies, we also knew that four technically feasible system alternatives were of interest: heat recovery incinerators, new replacement boilers, boilers modified to burn WDF in one or more forms, and hybrid waste-to-fuel-to-boiler conversion (e.g., plant conversions employing pyrolysis). It was necessary to establish a classification typology that contained the essential functional characteristics of both the existing systems and the alternative systems.

Finally, note that the energy conversion classification scheme was to contribute to the representation of an entire solid waste/resource recovery system; a classification system for the energy conversion subsystem that did not fit in the total system typology would not be useful to this project. Compatibility between the classification scheme for the energy conversion components and other system components required close cooperation among project team members in developing the scenarios and the candidate systems.

The classification scheme for the energy conversion system that evolved was keyed to two characteristics--"size of activity" and "type of fuel." To measure "size of activity" in terms relevant to this project, two criteria were used: (1) the quantity of solid waste generated, and (2) the steam load or fuel demand of the energy system. Because we were principally interested insofar as solid waste/resource recovery was concerned in WDF, we elected to use the solid waste generation rate as a single indicator of "size." The solid waste generation daily rates selected were 0-20 T/D_5,* 21-50 T/D_5, 51-100 T/D_5, and >101 T/D_5; it appeared that these classes adequately covered the Navy activities individually or grouped in complexes.†

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*T/D_5 = ton/day for a 5-day week.

†A "complex" as used here is a major Navy activity (serving as host), plus tenant activities and smaller nearby dependent activities.

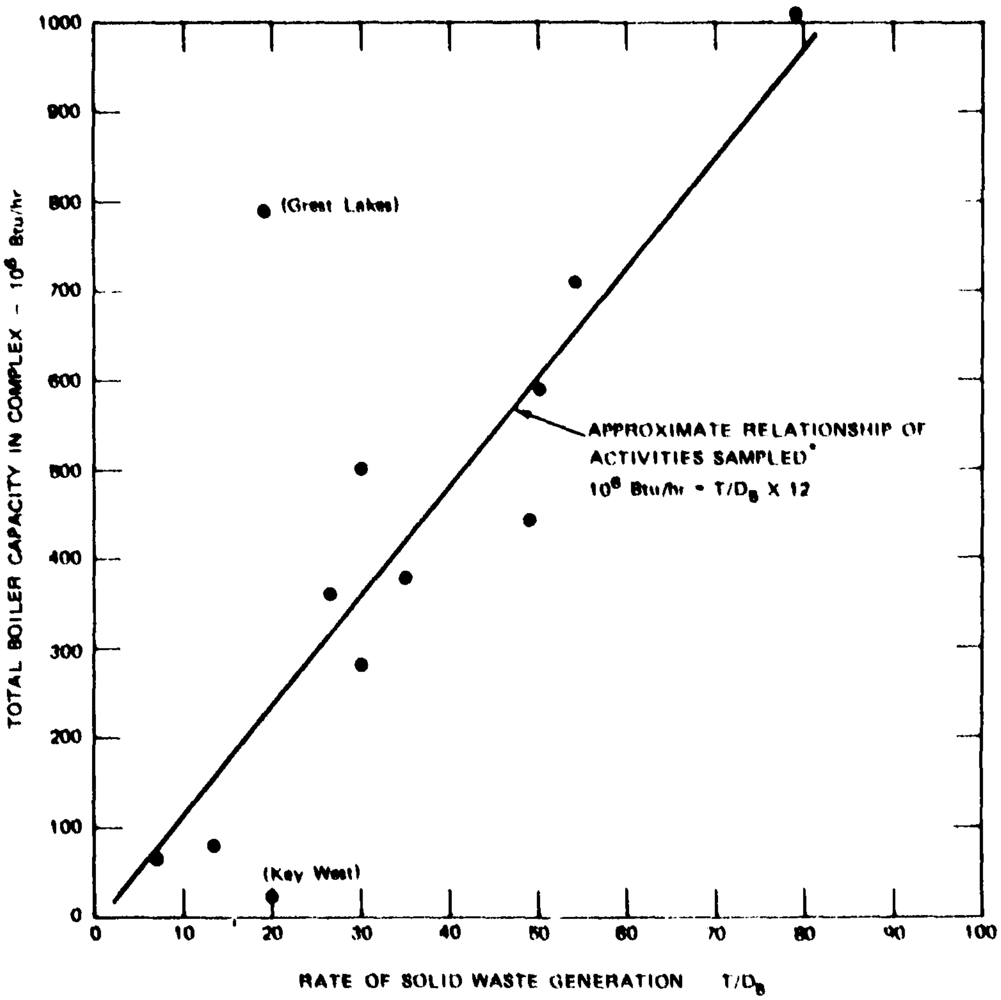
Converting solid waste indicators (T/D_5) into fuel demand size indicators (10^6 Btu/hr) for use with energy conversion plants and boilers required the use of indirect relationships. We had observed that plant solid waste generation rate and boiler plant size were probably related, as shown in Figure 7, and also that boiler plant size and average monthly plant fuel demand were positively correlated (see Figure 5). On the basis of these relationships, we concluded that, as a first approximation for use in this study, the fuel demand to solid waste relationship could be expressed by:

$$\frac{\text{Plant fuel demand } (10^6 \text{ Btu/hr})}{\text{Plant solid waste generation rate } (T/D_5)} \approx 4 \quad .$$

Using this relationship, plant fuel demand classes of $<80 \times 10^6$ Btu/hr, $81\text{-}200 \times 10^6$ Btu/hr, $201\text{-}400 \times 10^6$ Btu/hr, and 401×10^6 Btu/hr were established to correspond with the solid waste classes selected (<20 T/D_5, 21-50 T/D_5, 51-100 T/D_5, and >101 T/D_5).

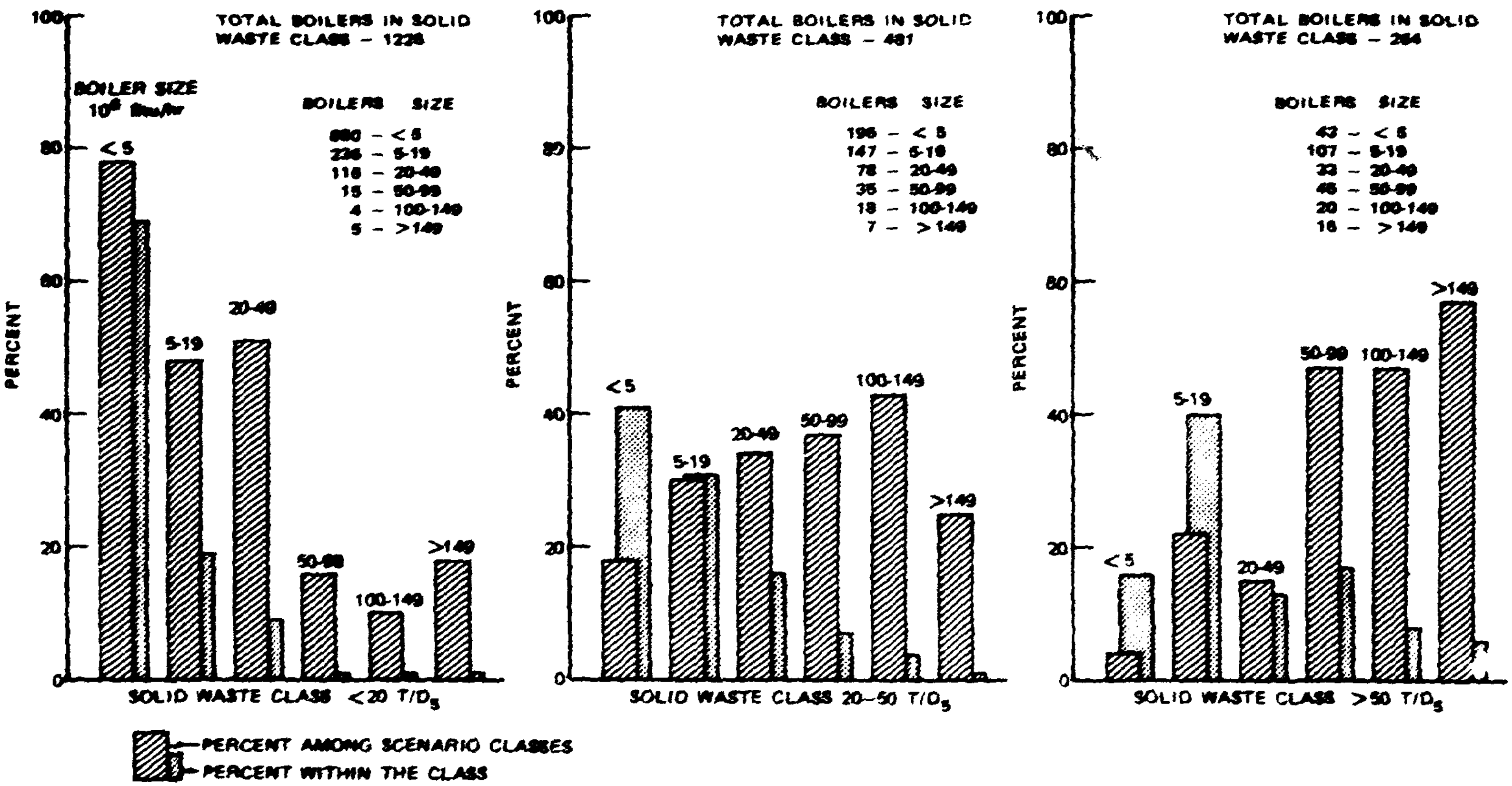
In addition to the fuel demand/solid waste relationship, the sizes of boilers represented by the solid waste classes in the classification scheme were of interest because a boiler's size was related to the possibility for converting its fuel. All of the boilers in each Navy complex were coded in class sizes as: $<5 \times 10^6$ Btu/hr, $5\text{-}19 \times 10^6$ Btu/hr, $20\text{-}49 \times 10^6$ Btu/hr, $50\text{-}99 \times 10^6$ Btu/hr, $100\text{-}149 \times 10^6$ Btu/hr, and $>149 \times 10^6$ Btu/hr. The distribution of these classes of boilers in three of the four classification size categories (i.e., the solid waste generation rate) is shown in Figure 8. Because the data in the >101 T/D_5 category were insufficient, that category was combined with the 51-100 T/D_5 class to make the >50 T/D_5 class.

The other characteristic selected for the energy conversion classification scheme was "type of fuel" (i.e., the primary fuel fired). Recognizing the differing potentials of coal-capable boilers and other boilers to use WDF in various forms, we decided that two classes of "type of fuel" should be tried--"coal" and "noncoal."



*A RANDOM SAMPLE OF 12 FROM 71 UIC's

FIGURE 7. BOILER PLANT CAPACITY VS. SOLID WASTE GENERATION RATE



Note: Boilers of less than .3 MMBtu/hr are not included

FIGURE 8. DISTRIBUTION OF BOILERS BY CAPACITY IN SCENARIO SOLID WASTE CLASSES

Combining the size criterion (four classes) and the type of fuel criterion (two classes) gave an energy conversion system classification scheme of eight classes (a 4 X 2 scheme).

IV NAVY ENERGY CONVERSION SYSTEMS IN CLASSES

Classifying the energy conversion systems by size and by the type of fuel consumed was a first step in solving the classification problem. To ascertain whether this scheme was applicable, it was applied to the Navy's existing energy boilers. The resulting classes were then examined to determine whether they could be considered the typical building blocks of future candidate options (i.e., systems typical of those that would be modified to utilize WDF in one or more forms).

A. Classification of Existing Boilers

Figure 9 indicates the distribution of existing Navy boilers among scenario classes under size and type-of-fuel consumed classifications. The preponderance of relatively small, noncoal boilers is significant.

Next, the Navy's coal conversion plans were projected for the existing boiler inventory, and the resulting distribution was calculated. Figure 10 shows the results. This figure illustrates how the coal conversion program focuses on large boilers and large waste generators. These large coal-firing boilers will certainly be system components for WDF utilization in one or more candidate systems.

B. Classification Scheme and Energy Conversion Options

The boilers classified as shown in Figure 10 are assumed to represent candidates for modification, augmentation, or replacement, after which they would represent energy conversion subsystem options in future solid waste/resource recovery systems. To analyze the total system, we needed to select the most technically feasible energy conversion subsystem options and to include them in the candidate future systems for comparison with current, unaltered operations.

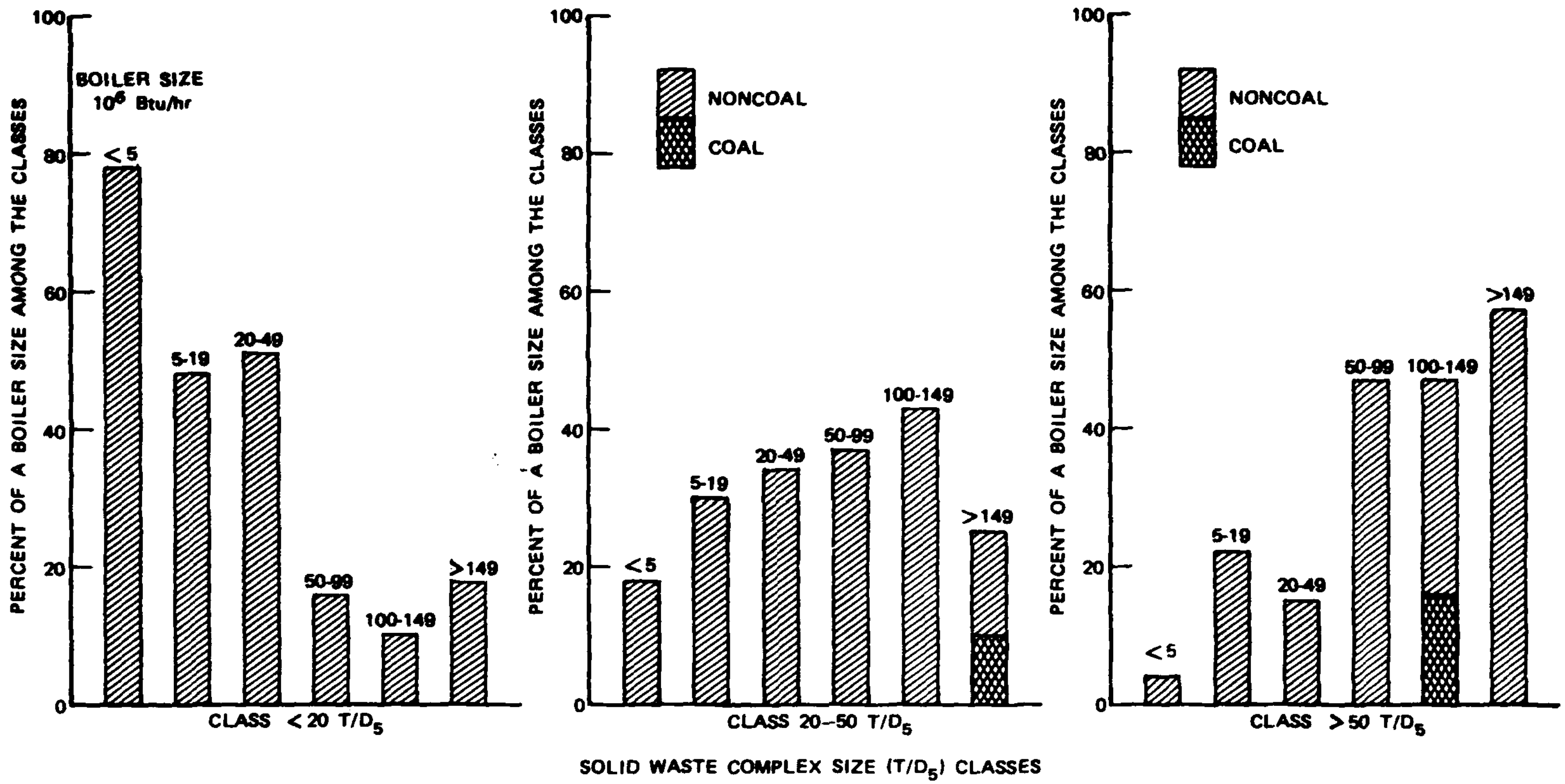


FIGURE 9. 1978 DISTRIBUTION OF BOILERS BY CAPACITY AND FUEL TYPE IN SCENARIO SOLID WASTE CLASSES

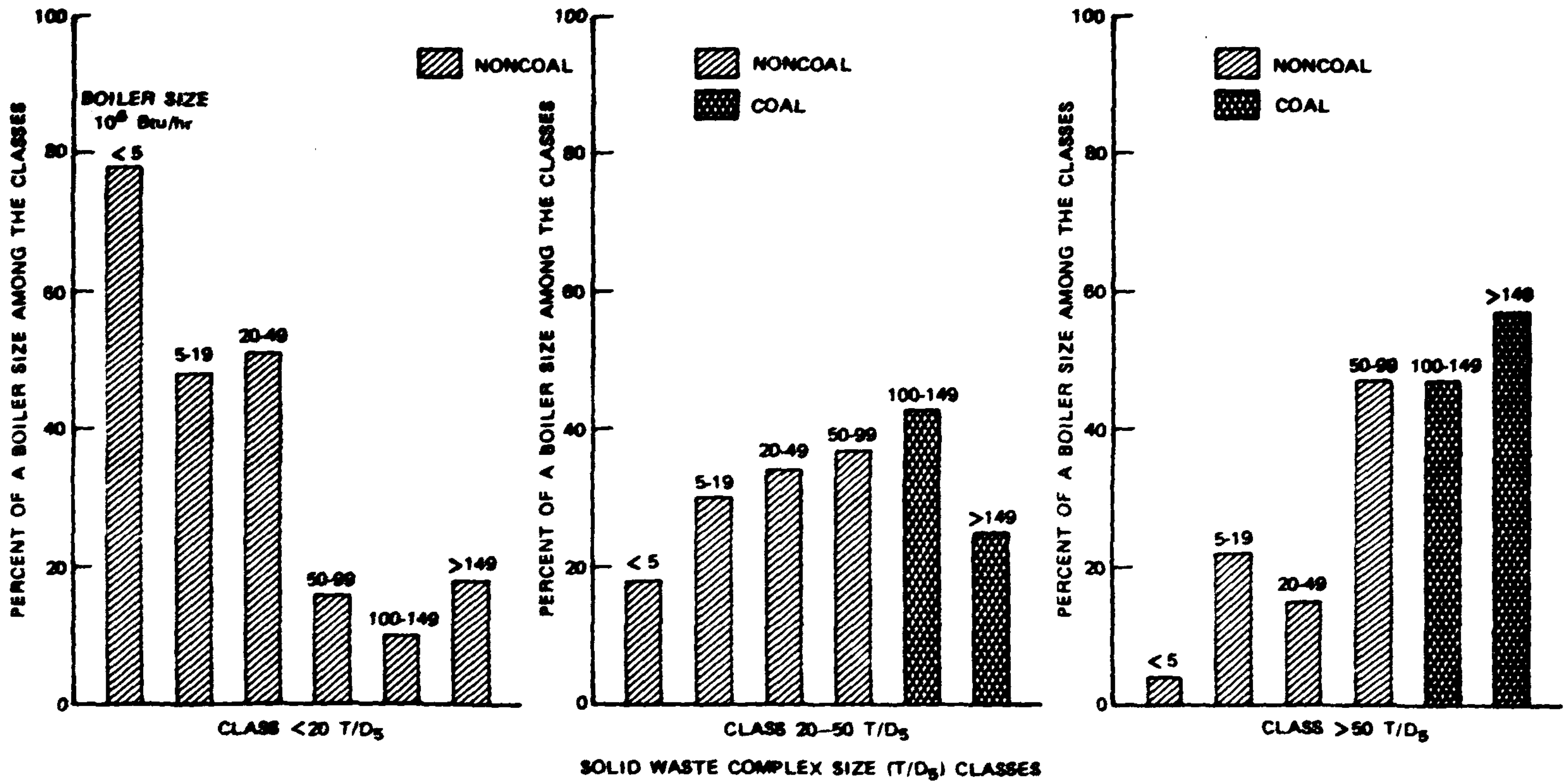


FIGURE 10. 1985 DISTRIBUTION OF BOILERS BY CAPACITY AND FUEL TYPE IN SCENARIO SOLID WASTE CLASSES

To judge whether the WDF energy conversion subsystem options were technically feasible, it was first necessary to review the technology of burning WDF in various forms as a function of boiler sizes and the form of WDF, as well as transforming the WDF into the fuel suited to a particular method of burning.

1. Incineration and WDF Preparation

Energy may be recovered from solid waste by mass burning (incineration) or by processing the waste into various fuels for subsequent burning in existing boilers. In theory, mass burning can be successful, both environmentally and insofar as solid waste disposal is concerned, with a minimum amount of preparation of the raw waste if the incinerator is properly designed to accept the particular waste. Heat recovery can improve the economics of incineration. Techniques for incineration have been improving for centuries and are continuing to advance, with increasing emphasis on improving heat recovery and pollution control. Recent studies of ways to improve heat recovery and to gain better control over air and water pollution have pointed to the desirability of a certain amount of preprocessing of the raw waste to remove objectional items and to make the waste more uniform in size and composition. More sophisticated methods of controlling air and feeding, as well as methods of stirring and ash handling, are also being developed to improve incinerator operation. The optimal compromise between preparing solid waste for the incinerator and tailoring the incinerator design to the waste form and composition has not been found; incineration still appears to be more art than science. Although relatively small package incinerators are being tried with various kinds of waste, only one form of incinerator--the waterwall incinerator--has been widely accepted in the United States for disposal of mixed solid waste. This type is suitable for large-scale installations (see Appendix A for a detailed analysis of the state of the art in incineration).

2. Conversions of Existing Systems and WDF Preparation

If incinerators were thought capable of providing cost-effective solutions to all energy recovery from solid waste needs, there would be little or no interest in developing processes to prepare fuels from the waste for use in existing (or modified) energy conversion systems. The motivation behind WDF preparation is to make a fuel from the waste that is compatible with the boiler and the primary fuels in order to make maximum use of existing heat recovery equipment, thereby avoiding as much as possible costly plant rearrangement or duplication of components.

It is technically possible to produce almost any form or kind of fuel from solid waste, but at present the economics of producing these fuels is very uncertain. Most of the processes are capital-intensive and have strong economies of scale. Because one of the purposes of processing the waste into WDF is to produce a product readily accepted as either a substitute or an augmentation fuel, a substantial cost-saving incentive is required to promote the use of the process. The ultimate goal in developing waste refining processes is to produce solids, liquids, and gases compatible with (or resembling) the primary fuels (i.e., coals, oils, and gases) conventionally used, and to use the refined waste as fuel thereby substantially lowering the total system costs. So far this has proven quite difficult. More refined WDF forms generally perform better and require less additional support equipment, but they cost significantly more per unit of energy. The trade-offs between the degree of processing and the amount of modification are quite complex because of interactions among functions in the refining and burning processes, and the economics of scale for modifications.

The methods developed to date to produce WDF usually involve to differing degrees the following first-stage processing steps: size reduction, removal of inert material, and classifications into combustible and noncombustible fractions. Several forms of what are commonly called "fluff RDF"* result. These fluffs can be processed further (second-stage

*RDF is an acronym for refuse derived fuels. RDF as used here refers to solid forms of WDF.

processing) by mechanical means into denser solid forms, chemically into dust solids, or thermally into liquids or gases. However, the physical and chemical properties of each of these solid, liquid, or gaseous forms of WDF can vary widely. One of the requirements in producing WDF is process control to ensure that the end product (produced from a complex, highly variable raw material) is usable or marketable. That is, it must be sufficiently uniform to be substituted for, or cofired with, a conventional fuel.

Isolating unit processes without regard to their interactions for the purpose of developing unit process technical or economic data has not been very successful. The controlled testing necessary has not been done.* Capital costs for the unit processes can be obtained from equipment vendors and architects and engineering firms, but estimating operating and maintenance costs per unit processes with any precision is impossible because no detailed records yet exist of system operations. Common practice at present is to set total system O&M costs at a percentage of the total capital cost. This approach was used for developing the incinerator costs shown in Appendix A and the costs of other alternatives discussed in Section V.

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*Midwest Research Institute, "Study of Preprocessing Equipment for Waste-to-Energy Systems," prepared for EPA Workshop, New Orleans (8-10 February 1977).

V POTENTIAL FOR CONVERTING SYSTEMS IN EACH CLASS TO USE ALTERNATIVE FORMS OF WASTE DERIVED FUELS

The energy conversion subsystem classes defined in the preceding chapter can be displayed in matrix form, as shown in Table 2.

Table 2

MATRIX OF ENERGY CONVERSION CLASSES

Plant Size (10^6 Btu/hr)	Type of Fuel (Primary) a. Coal	b. Noncoal
1. <80		
2. 81-200		
3. 201-400		
4. >401		

The alternative forms of WDF that are considered feasible to produce (or purchase) within the next 5 years are:

Solids--(1) raw; (2) fluff; (3) dust; (4) densified

Liquids--(1) highly oxygenated pyrolytic oils; (2) low oxygen content oils

Gases--(1) low-Btu; (2) medium-Btu; (3) high-Btu.

Current literature on cofiring WDF indicates that cofiring any of the processed forms of WDF (excluding raw solid waste) with coal in coal-capable boilers is technically feasible, regardless of the size of the boiler. But conversion requirements must also be considered because extensive additions or modifications may be required to accommodate some forms of WDF in a given plant. Navy plants capable of firing coal within the next 10 years have capacities greater than 200×10^6 Btu/hr.* (Of

*A plant is assumed to have multiple boilers. Therefore boiler sizes below 100×10^6 Btu/hr were disregarded as candidates for coal conversion.

the 20 plants operating or planned, 8 will have capacities greater than 400×10^6 Btu/hr.) The potential for converting these larger plants to use WDF is rated as moderate to high, depending on the form of WDF under consideration. The two smaller coal classes will be deleted because no plans exist for coal-capable Navy boilers in those classes.

For noncoal plants, few constraints, if any, are foreseen on firing or cofiring liquid or gaseous WDF in these plants, regardless of their size. Burning characteristics of low-Btu gases may, however, so decrease the capacities of smaller plants firing these gases that they could not meet the peak loads. (Smaller systems usually have less excess capacity to meet peak loads.) One factor to consider in rating the potential for converting noncoal boilers to fire liquid WDF is that the smaller plants are most frequently designed to burn distillate only, whereas the larger plants may be set up to fire either residual or distillate oils. For this reason, the potential for firing low-oxygen WDF liquids appears greater (the method is more universally acceptable and has fewer fuel heating and pumping problems) than the potential for firing highly oxygenated WDF liquids. Nevertheless, the potentials for both are judged to be high.

Burning solid forms of WDF in noncoal boilers is now undergoing considerable research. Technical feasibility has been demonstrated at several large industrial plants that fire fluff and dust, but problems related to arrangements for ash handling and particulate control can be difficult and expensive to solve, especially at smaller plants. The Gilbert/Commonwealth report contains a case study of a typical medium-sized, oil-fired plant base loaded on fluff WDF. Simplified conceptual firing arrangements are presented, and the capital cost estimates appear to be attractive. The costs of this method are discussed in the next section and covered in detail in that report.

Judgments concerning the technical feasibility of utilizing various forms of WDF in the Navy's boiler plants can be entered into the matrix of classes (Table 2) with the results presented in Table 3.

Table 3

JUDGMENTAL RATINGS OF WDF POTENTIAL BY ENERGY CONVERSION CLASSES

Plant Size (10^6 Btu/hr)	Type of Fuel Primary: a. Coal	Type of Fuel Primary: b. Noncoal
1. <80	N.A.	$\boxed{\text{L-1,2}}$ (G-3)
2. 80-200	N.A.	$\boxed{\text{L-1,2}}$ (G-2,3)
3. 200-400	(S-2,3,4) $\boxed{\text{L-1,2}}$ (G-3)	(S-2,3) $\boxed{\text{L-1,2}}$ (G-2,3)
4. >400	(S-2,3,4) $\boxed{\text{L-1,2}}$ (G-2,3)	(S-2,3) $\boxed{\text{L-1,2}}$ (G-2,3)

Key to WDF type: Solid

S-1, raw; S-2, fluffs; S-3, dust; S-4, densified

Liquid

L-1, highly oxygenated pyrolytic oils; L-2, low oxygen content oils

Gases

G-1, low-Btu; G-2, medium-Btu; G-3, high-Btu

Rating: $\boxed{\quad}$, high; ( ), moderate. Poor and unacceptable ratings have been omitted.

Table 3 shows that a clear preference exists for the liquid WDF (pyroils) in all classes. This preference results from the relatively high energy density (Btu/lb), apparent ease of handling, and relatively low ash content of pyroils--all of which contribute to minimizing the clean-up, blow-down, and pollution-control requirements of the conversions.

We emphasize that the preference for pyroils indicated in Table 3 is not based on pyroil fuel costs or total system economics of systems using pyroils. At present, no processes have been developed that have a reasonable chance of producing pyroil in the near term at a price competitive with projected prices of petroleum. Although it is potentially

attractive, widespread utilization of liquid WDF will depend on significantly reducing its costs. In the near to intermediate term, if special site conditions (e.g., a large number of small oil-fired boilers in a region with stringent air standards) require an unusual solution, pyroil might be attractive in the total solid waste/resource recovery system. Pyroils are discussed further in the next section, in Appendix A, and in the Gilbert/Commonwealth report.

VI DIFFICULTIES AND COSTS OF IMPLEMENTING ALTERNATIVES

The classification scheme developed for this study tends to mask individual features of the Navy's boiler plants; each plant, in fact, is unique in many ways. On the other hand, boilers within the classes we have defined present common problems, similar modification requirements, and typical costs as energy conversion alternatives. Knowledge of these class-related traits should help narrow the field of investigation required for efficient analyses of candidates in subsequent detailed design studies for a given class. Such knowledge also enables gross comparisons among classes to be made for R&D planning purposes. The discussion that follows, therefore, identifies what is known or can be estimated from analyzing data from numerous sources and then generalizes the information so that it may be applied to the energy systems in the classes we have selected.

More than 200 articles, papers, and books (see Chapter VII, Bibliography) were screened for relevant technical and economic information about alternative actual or conceptual resource recovery systems. Data were abstracted and compiled by the functional segments of a solid waste/resource recovery system (i.e., by generation, collection, transport, compaction, size reduction, classification, fuel recovery, energy conversion, disposal, and marketing). SRI project staff members reviewed the data in their areas of expertise and, when possible, extracted information from the compiled references that was appropriate to the "size/type of fuel consumed" classes selected.

Together with this survey and the literature review, two special studies were performed:* (1) mass burning of solid waste with heat recovery in shop fabricated incinerators (package incinerators), and (2) waste fuel utilization by conversion of existing Navy steam plants. These

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*See Appendix A and Gilbert/Commonwealth report.

two alternatives were of immediate interest to the Navy and thus deserved particular attention.

Information acquired through these two studies was combined with the information retrieved from the references to form a substantial data base on energy recovery systems and conversion alternatives. The alternatives considered belonged to four general categories:

- Heat recovery incinerators
- New or replacement boilers capable of burning WDF
- Boilers modified to burn WDF
- Hybrid conversions (pyrolysis and "hot smoke" generators, plus existing boilers).

The modifications, costs, and other problems associated with implementing each of these alternatives are discussed in the following sections. A later section compares cost data. Suggestions concerning RDT&E that might help solve some of the problems identified are offered in the final section of this chapter.

A. Heat Recovery Incinerators

Waterwall incinerators are appropriate for larger class systems ($>400 \times 10^6$ Btu/hr); they can generate large quantities of high quality steam, but they are also capital-intensive and require a major commitment of space and manpower. Other problems exist as well. First, when they run on raw waste, the incinerators generate unpredictable air and water pollutants, which may be difficult and expensive to control. Second, process control is insufficient to meet rapidly fluctuating demand. Unless steam demand is substantial and relatively steady year round, it is unlikely that a waterwall incinerator could be cost-effective.

A Navy complex that has coal-burning capability might find the waterwall incinerator a competitor to modifying the plant to cofire WDF if enough waste from the nearby federal activities or surrounding communities were available. In addition, under the same conditions, a waterwall incinerator could be a strong competitor with a noncoal complex.

Package incinerators are appropriate alternatives to be considered for the smaller complexes or isolated activities. Still relatively unproven under relevant Navy operating conditions, they are nevertheless important candidates for the future because their technology is advancing rapidly. Investment costs of package incinerators are comparatively modest, and for medium sizes estimated O&M costs are reasonable. Adhering to air pollution regulations in most regions does not appear to be a problem, but some questions have arisen concerning disposal of residues in cases of incomplete burnout.

Package incinerators should be considered as alternatives for all systems except, possibly, the largest, >100 T/D_5.

B. New or Replacement Boilers Capable of Burning WDF

DOD* design criteria for boiler and hot water heater fuel selection are shown in Table 4. The basic intent of the ASD memorandum from which this table was extracted was to reduce the use of natural gas in DOD heating plants. A further objective was to reduce dependence or reliance on any single form of fuel, and on natural gas in particular.

The criteria given in Table 4 are intended to encourage development of dual fuel (oil/solid) capability in size categories from 5×10^6 Btu/hr to 150×10^6 Btu/hr, and solid fuel capability for boilers with capacities 150×10^6 Btu/hr or more. This directive mandates that liquid and solid WDF must be considered candidate fuels in new or replacement boilers in all the classes we have selected for study.

The Navy is implementing these instructions aggressively, giving priority to coal utilization at its major plants. Because the basic designs of these new boiler plants must accommodate ash handling, dust suppression, and particulate control, it should be relatively easy to add equipment to fire WDF in some form, although the added costs may be significant. However, cofiring of WDF of characteristically low sulfur

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*ASD I&L Memo (8 April 1976).

Table 4

DESIGN SELECTION FOR BOILER PLANT FUELS
[For All New Planned and Existing NG or Dual (NG-Fuel Oil) Plants]

Plant Capacities			
5×10^6 Btu/hr and as high as 50×10^6 Btu/hr	50×10^6 Btu/hr and as high as 100×10^6 Btu/hr	100×10^6 Btu/hr and as high as 150×10^6 Btu/hr	150×10^6 Btu/hr and above
New Construction Including Expansions and Additions			
Unit Options: (1) Fuel oil (2) Dual (fuel oil-solid fuel) (3) Solid (coal, refuse, RDF or any combination thereof)	Unit Options: (1) Solid fuel (2) Dual (fuel oil-solid fuel) (3) Fuel oil	Unit Options: (1) Solid fuel (2) Dual (fuel oil-solid fuel)	Unit Option: Solid fuel
Replacements or Conversions			
Unit Options: (1) Fuel oil (2) Dual (fuel oil-solid fuel) (3) Solid (coal, refuse, RDF or any combination thereof)	Unit Options: (1) Solid fuel (2) Dual (fuel oil-solid fuel) (3) Fuel oil	Unit Options: (1) Solid fuel (2) Dual (fuel oil or solid fuel) (3) Fuel oil with provision for solid fuel in future	Unit Option: Solid fuel

A. Plants or units of 5×10^6 Btu/hr to 20×10^6 Btu/hr must be capable of burning all grades of fuel oil through at least No. 5 oil.

B. Oil burning equipment for units or plants of 20×10^6 Btu/hr and above must be capable of burning all grades of fuel oil through No. 6. This requirement is not applicable where oil is the alternate fuel in a dual-fuel unit.

C. When solid fuel only is indicated and fuel transportation and/or supply of the required fuel (e.g., low-sulfur coal) is infeasible, the plant or unit may be constructed with a dual (solid fuel-fuel oil) burning capability with ASD (I&L) approval.

D. The Defense Fuel Supply Center will be contacted in writing regarding coal availability before the design of a coal burning unit and/or plant is approved.

E. All units in a new plant will have the same fuel-burning design.

Definitions: Unit: Individual boiler or hot water generator. 10^6 Btu/hr: Million Btu per hour output capacity. Solid Fuel: Coal, refuse, RDF, or any combination thereof. RDF: Refuse derived fuel. NG: Natural gas.

Source: ASD I&L Memo (8 April 1976)

content may actually improve the cost effectiveness of new coal firing systems in some instances by reducing the sulfur concentrations in the stack gases, thereby enabling the plants to fire high-sulfur coals with less costly stack gas cleanup equipment.

C. Boilers Modified to Burn WDF

The problems, modifications, and costs associated with converting existing boilers to fire WDF are (1) site-specific and (2) a function of original boiler type. However, some general comments on this alternative may be useful, especially in suggesting the effects of the scale of the plant, the size of the boilers, and the type of cofiring contemplated.

Converting plants already capable of burning coal to any form of WDF should not be technically difficult. Conversion for liquid or gaseous forms would probably be straightforward and would be less expensive than conversion for solid forms. (Oil and gas firing systems are simpler than counterpart systems for solids.) However, converting to solid forms might be more cost-effective for larger systems because their fuel cost/ton will probably be lower.

Reconverting plants previously capable of burning coal back to solid fuels is a priority Navy program. Compared with boilers already capable of burning coal, adapting these conversions for use with WDF may present some added problems, depending on how the boilers and support equipment were converted from coal burning to oil or gas. As discussed in a NAVFAC working paper,* in some plants much of the support equipment for coal burning was left in place (in various states of repair); in others, however, the spur lines, unloading platforms, conveyors, and so on were removed and the areas were used for other purposes. In some cases, the furnace grates were removed but saved; in others, the furnace bottoms were bricked up. Detailed studies of these plants are currently under way. Table 1, page 14, lists plants now planned to be converted to coal.

*A study by Hoffman/Munter Associates for NAVFAC Code 102.

It is, of course, possible to cofire liquid or gas WDF with coal in reconverted plants. In general, if coal reconversion is only marginally cost-effective, cofiring liquid or gaseous WDF might be attractive options, if it is assumed that Btu costs for WDF fuels are lower and if cofiring reduces air pollution equipment costs.

Although much attention is being paid to increasing coal burning capabilities throughout the Navy, most medium-sized plants will burn oil or gas for many years to come. Converting these boilers to burn WDF liquids or gases may not be particularly difficult or costly, but the availability of these forms of WDF in sufficient quantity at competitive prices is questionable.

The technology assessment in the Gilbert/Commonwealth report addresses the use of fluff WDF in a modified oil-fired boiler, and identifies the problems that would be encountered, the modifications required, and the typical capital costs for equipment. Site-related conditions tending to favor the adoption of this alternative are also outlined.

D. Hybrid Conversions

A number of other combinations of solid-waste-to-fuel-to-energy-conversion systems are possible. For example, a gasifying pyrolysis unit producing fuel from an activity's waste could be used in a feedwater preheater (economizer), and a package incinerator generating "hot smoke" could be used in the boiler or the superheater. Some of these alternatives might be of interest if more technical and cost information were available on the pyrolytic and incinerator "full generating" processes. Appendix A presents information about costs of package incinerators without heat recovery and an overview of the available information on pyrolysis processes.

The CPU 400 system, a concept under development for solid waste to electricity in one unified design, is not covered in this study. From the beginning, technical problems have plagued this method of using the hot gases from solid-waste-fueled fluidized bed combustion (FBC) to drive a gas turbine generator. Advanced experiments with FBC are planned by

the Navy and DOE at the Great Lakes U.S. Naval Training Station. Further development may make FBC a practicable alternative for firing solid fuels, including solid wastes, to release heat or generate steam. When more data on these systems are available, they should be included in the data base of this project.

E. Economic Comparisons

The economic data obtained from the various sources and from the two special studies are of particular interest. Summary comparisons of these cost data are provided below. Costs extracted from the literature survey are given in Table 5.

The investment cost per ton day capacity ($\$/TD_5$) has frequently been used to indicate the relative costs and the sensitivity to scale of various alternatives. Figures 11 and 12* are examples of this indicator.

Figures 13 and 14* illustrate the total net annual costs of shop-fabricated incinerators as a function of size and the cost impact of particulate control. The costs depicted include capital recovery and O&M costs. No credits are assumed for landfill cost reduction.

The capital cost data for the Case Study of the Gilbert/Commonwealth report (conversion of a typical existing oil/gas plant to cofire fluff RDF) are summarized in Table 6. These estimates of capital costs were prepared by Gilbert/Commonwealth for a plant firing RDF prepared from approximately 120 tons of waste each day. This would indicate a capital cost per ton-day capacity of $14,500, a very attractive cost compared with the costs of other alternatives (see Figures 11 and 12).

On the basis of these capital costs, SRI calculated estimates of other costs. These estimates are shown in Table 7. The break-even point for this particular conceptual system was then calculated to determine the price that could be paid (or the production costs that could be incurred) for the RDF. Table 8 indicates this calculation.

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*See Appendix A for supporting details.

Table 5

ECONOMIC DATA FROM STUDIES ANALYZED

Candidate System Description	Capacity (T/D)	Activity (Location)	Candidate Number	Costs* ($/ton)	Credits ($/ton†) Fe	Al	NonFe	Electricity	Steam	Net‡ ($/ton)	Energy Output (10^6 Btu per hr/ days per week)
Incineration, hot gases to existing boiler, no pollution control	20	Crane, Indiana	3	100	0	0	0	0	34.92	77.68	9/5
RDF in new spreader, stoker boiler with baghouse	35	Bremerton, Washington	15	117	0	0	0	0	25.92	103.78	12/5
Incinerator with heat recovery boiler, baghouse	35	Bremerton, Washington	16, 17	90	0	0	0	0	21.60	81.10	10/5
Two-stoker waterwall incinerators	95	Mayport, Florida	2	42	0	0	0	0	24.67	24.03	31/5
Two-waterwall incinerators	115	Charleston, West Virginia	2	62	1.10	0	0	0	21.47	44.98	49/5**
RDF in modified boiler	135	Ft. Bragg, North Carolina	3	32	0.71	0	0	0	26.32	10.52	46/5
RDF in modified boiler, with cogeneration	135	Ft. Bragg, North Carolina	3	48	0.71	0	0	10.26	26.32	16.26	46/5
Coarse RDF in new spreader, stoker boiler with baghouse	145	Mare Island, California	7	64	0	0	0	0	16.05	54.50	22/7
Dust RDF in suspension, boiler with baghouse	145	Mare Island, California	(7)§	68	0	0	0	0	16.06	54.49	22/7
RDF in modified boiler	235	Ft. Bragg, North Carolina	3	29	0.74	0	0	0	24.77	9.04	55/7
RDF in modified boiler, with cogeneration	235	Ft. Bragg, North Carolina	3	41	0.74	0	0	6.88	24.77	14.17	55/7
Two-waterwall incinerators	305	Charleston, West Virginia	2	32	0	0	0	0	17.63	17.72	100/6**
Coarse RDF in new spreader, stoker boiler with baghouse	350	Mare Island, California	7	44	1.58	2.01	0	0	14.52	31.44	48/7
Dust RDF in suspension, boiler with baghouse	350	Mare Island, California	(7)§	47	1.58	2.01	0	0	14.52	34.44	48/7
Two-waterwall incinerators	375	Charleston, West Virginia	2	27	0	0	0	0	25.16	12.39	100/5
RDF in new stoker boiler with electrostatic precipitation	590	Sacramento, California	7	37	2.14	0	3.06	0	15.88	21.54	75/7
RDF in modified boiler	600	Ft. Bragg, North Carolina	3	17	0.58	0	0	0	17.11	4.88	96/7
RDF in modified boiler, with cogeneration	600	Ft. Bragg, North Carolina	3	20	0.58	0	0	4.62	17.11	3.25	96/7

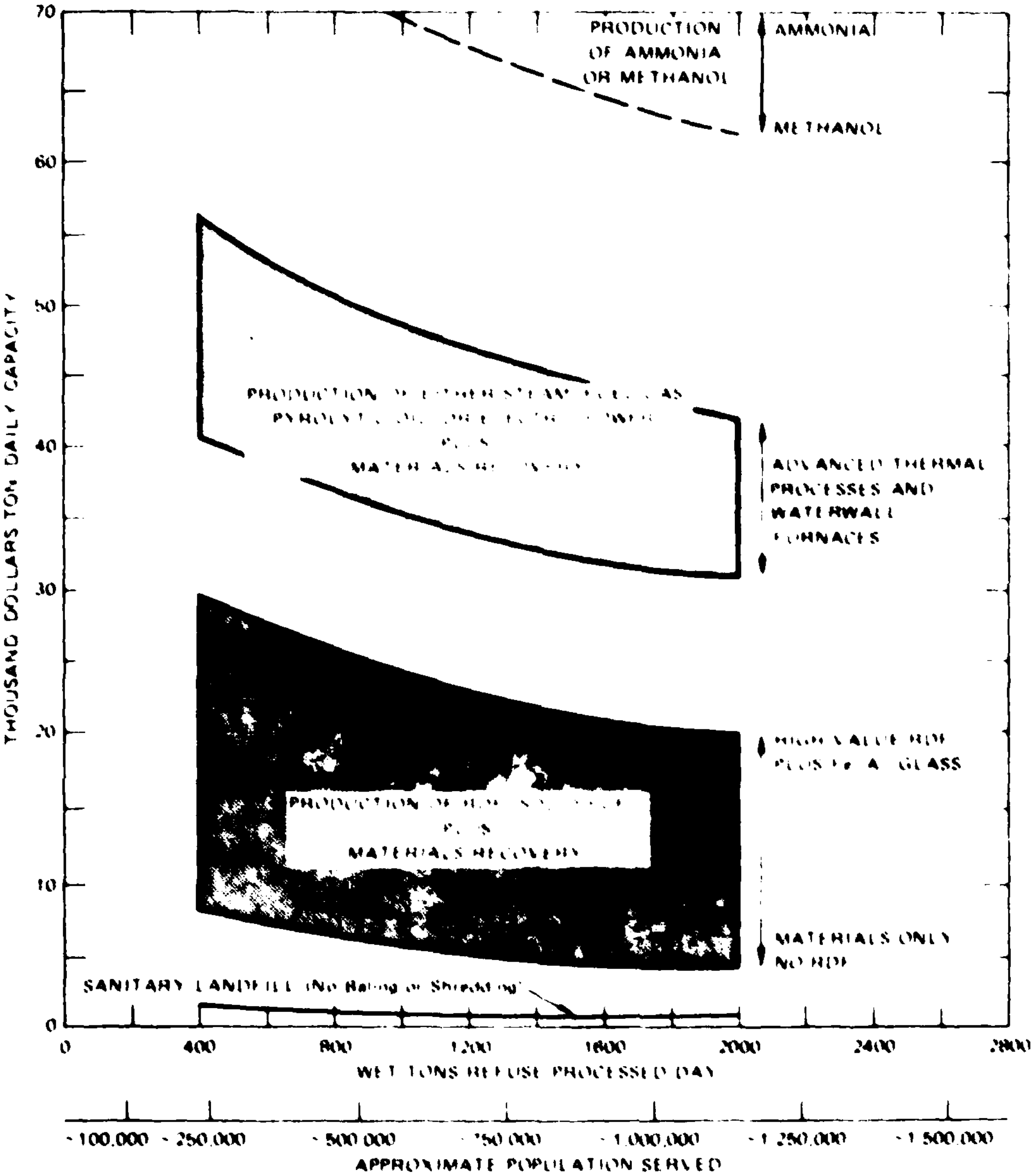
*O&M + capital recovery.

†No credits taken for landfill cost reduction.

‡As operated, potential net costs.

§Dust in suspension not a priority candidate.

**16-hour operation day.



NOTE Mid-1978 costs
SOURCE SRI International

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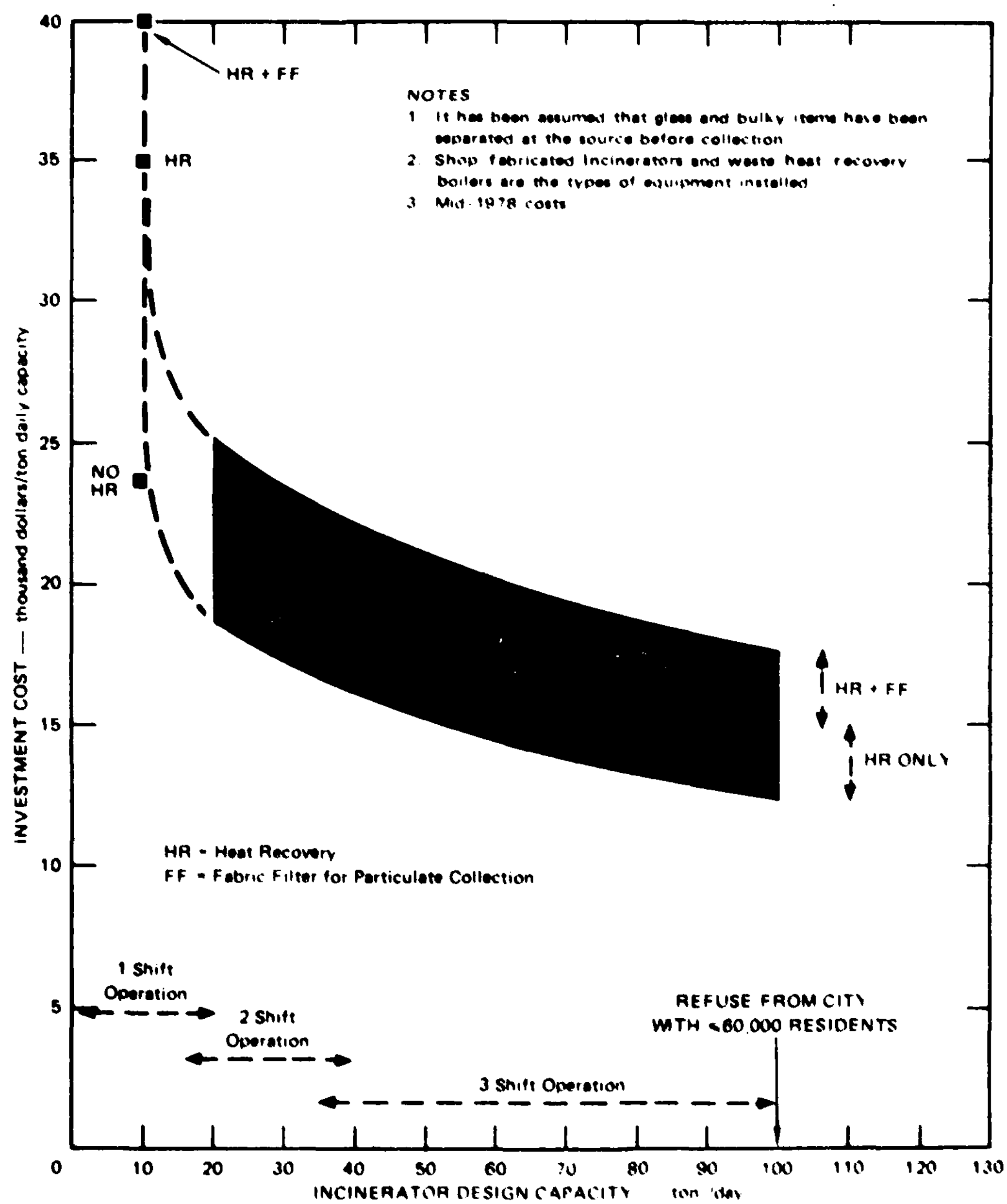
FIGURE 11. APPROXIMATION OF RELATIVE INVESTMENT REQUIREMENTS BASED ON ACTUAL AND ESTIMATED COSTS FOR LARGE REFUSE PROCESSING FACILITIES



SOURCE SRI International SA 7332 3

FIGURE 12. APPROXIMATION OF INVESTMENT REQUIREMENTS FOR SMALL REFUSE INCINERATION FACILITIES WITH HEAT RECOVERY

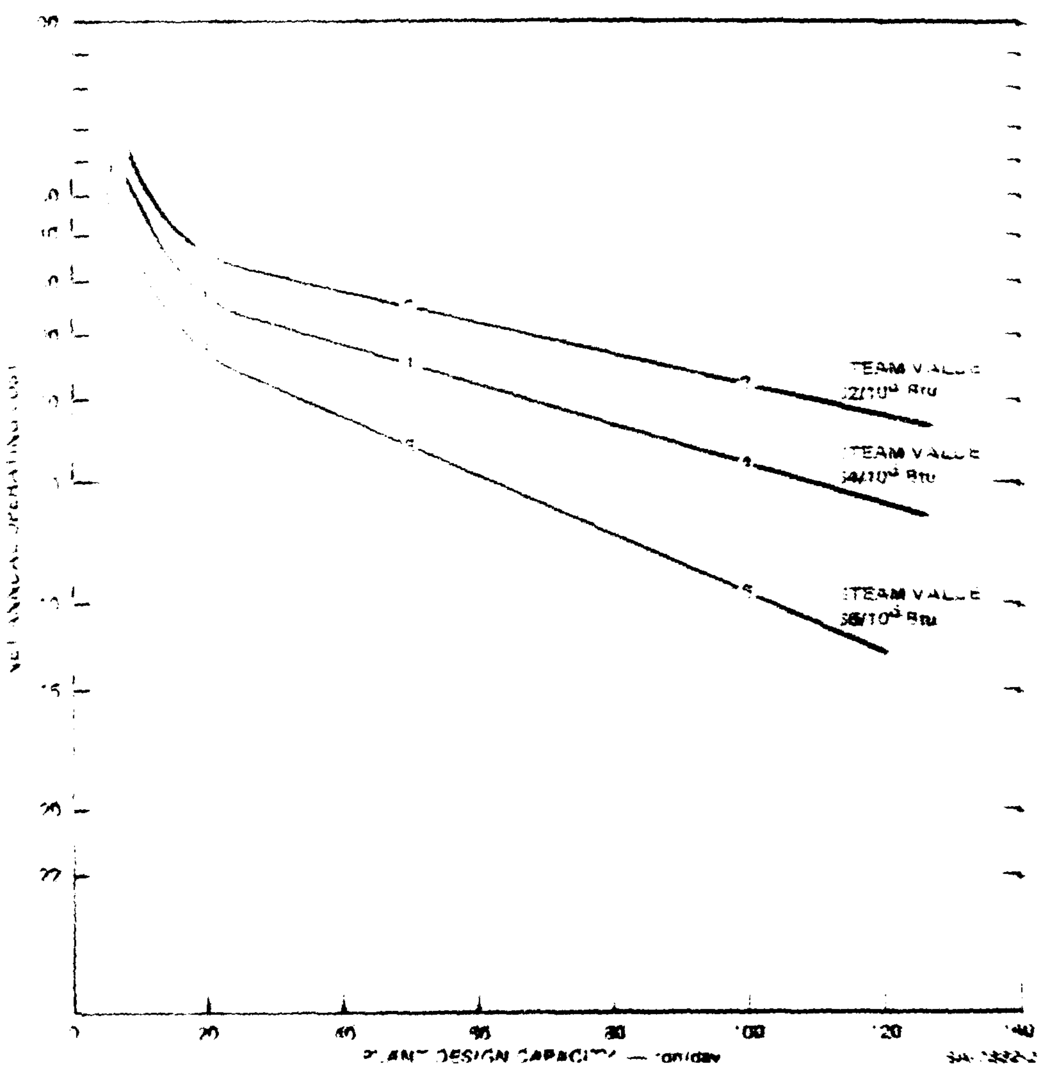


FIGURE 13 NET ANNUAL OPERATING COST AS A FUNCTION OF PLANT DESIGN CAPACITY WITH NO PARTICULATE COLLECTION

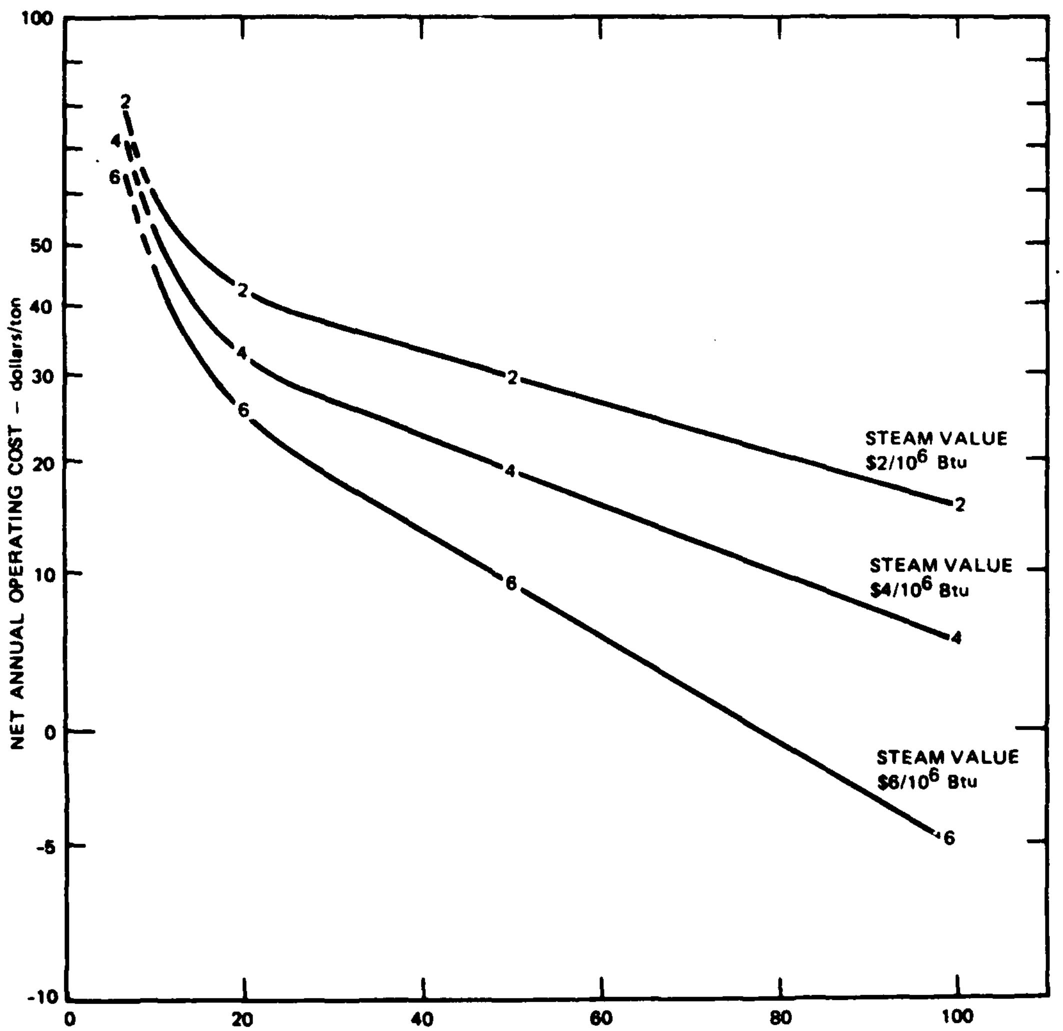


FIGURE 14. NET ANNUAL OPERATING COST AS A FUNCTION OF PLANT DESIGN CAPACITY WITH PARTICULATE COLLECTION

Table 6

ESTIMATED* CAPITAL COSTS OF CONVERTING AN EXISTING
250×10^6 Btu/hr NAVY OIL FIRED PLANT TO
COFIRE FLUFF RDF

Direct Costs	Thousands of Dollars	Approximate Percent of Total
Structural	174	10
Fluff unloading equipment	93	5
Pneumatic conveyor	417	24
Boiler modifications	258	15
Dust collectors	84	5
Instrumentation	20	1
Electrical	70	4
Total direct	$1,116	64
Field indirect	143	8
Total construction	$1,259	72
Engineering	188	11
Contingency	289	17
Total	$1,736	100

*See Gilbert/Commonwealth report, Table 3.1.3.2 for Cost Estimate ground rules.

Figure 15 illustrates representative net annual savings as a function of cost of RDF for this conceptual system. Estimates are given for the base-case capital cost and for 1.5 and 2.0 times the base case capital costs to indicate the sensitivity of net annual savings to capital :ost.

We can assume that this system uses the solid waste from the case study activity (plus other wastes) and that any oil savings will be credited to the solid waste/resource recovery system to offset the tipping fee for the ash. Under these conditions, we might want to know what tipping fees these savings could offset (tipping fee breakeven points). A conservative estimate of the cost of fluff is approximately $\$1.00/10^6$ Btu

Table 7

ESTIMATED ANNUAL OPERATING COSTS FOR MODIFIED OIL-FIRED BOILERS*

Function	Approximate Amount (dollars)
Ash disposal (~4,200 tons/yr × $10.75/ton)	45,000
Labor†	
Operating labor (1/2 man/shift at $6/hr)	30,000
Payroll burden	9,000
Total Operating Labor	39,000
Maintenance (labor and supplies)	50,000‡
Electric power	20,000§
Direct charges (excluding purchase of RDF)	154,000
Capital charges (at discount rate of 10%) for project life of 25 years	191,000
Total Annual Costs (excluding purchase of RDF)	345,000

*Cost of RDF is excluded; boiler is assumed to burn fluff RDF at a rate equivalent to 20% of Btu input capacity.

†Assumes that no additional supervisory labor or administrative labor is required. Some installations may be able to use existing employees to supervise RDF unloading, ash dumping, and boiler inspection.

‡Average annual maintenance cost estimate includes consideration of the following: Replacement of dust collector, maintenance and replacement of augers in live bottom bins, maintenance and replacement of equipment in unloading area, maintenance for fixing or patching furnace refractory replacement grates, maintenance on rotary valves. $50,000/year is equivalent to ~2.5% of the estimated capital investment for the modification to allow RDF firing.

§120 ton/day × 15 kWh/ton × 360 day/yr = 648,000 kWh/yr; 648,000 kWh/yr × $0.03/kWh ≅ $20,000/yr.

Table 8

BREAKEVEN POINT FOR CASE STUDY BOILERS
(Thousands of Dollars)

Annual operating costs minus costs of RDF	154
Capital recovery annual costs	191
Total annual costs, less costs of RDF	345
Annual savings in oil costs by firing RDF (79,000 bbl saved at $14.70/bbl)	1,160
Amount available for purchase of RDF	815
Breakeven price for RDF $815,000 + 43,000 ton/yr)	19.00/ton

or an annual saving of about $200,000 (as shown in Figure 14). If we apply this annual oil saving to annual tipping fees, we find that, if 4,200 ton/yr of ashes are disposed of, tipping fees could be $47.60/ton and the system would still break even.

F. Suggestions for RDT&E

To help solve problems that the Navy may encounter in pursuit of resource recovery from solid waste, the following suggestions for RDT&E are offered:

- A review of Navy solid waste components that could emit significant quantities of noncriteria air pollutants during combustion.
- A preliminary technical/economic evaluation of a fluidized bed combustor (preceded only by a trommel and shredder) for solid waste combustion at Naval installations with >50 ton/day of solid waste.
- A study of the operating characteristics, performance, and investment and operating costs for particulate control devices for small capacity solid waste combustion units (20 to 200 ton/day).
- A study of the costs of controlling nuisance odor problems at resource recovery plants by scrubbing building ventilation system exhaust.

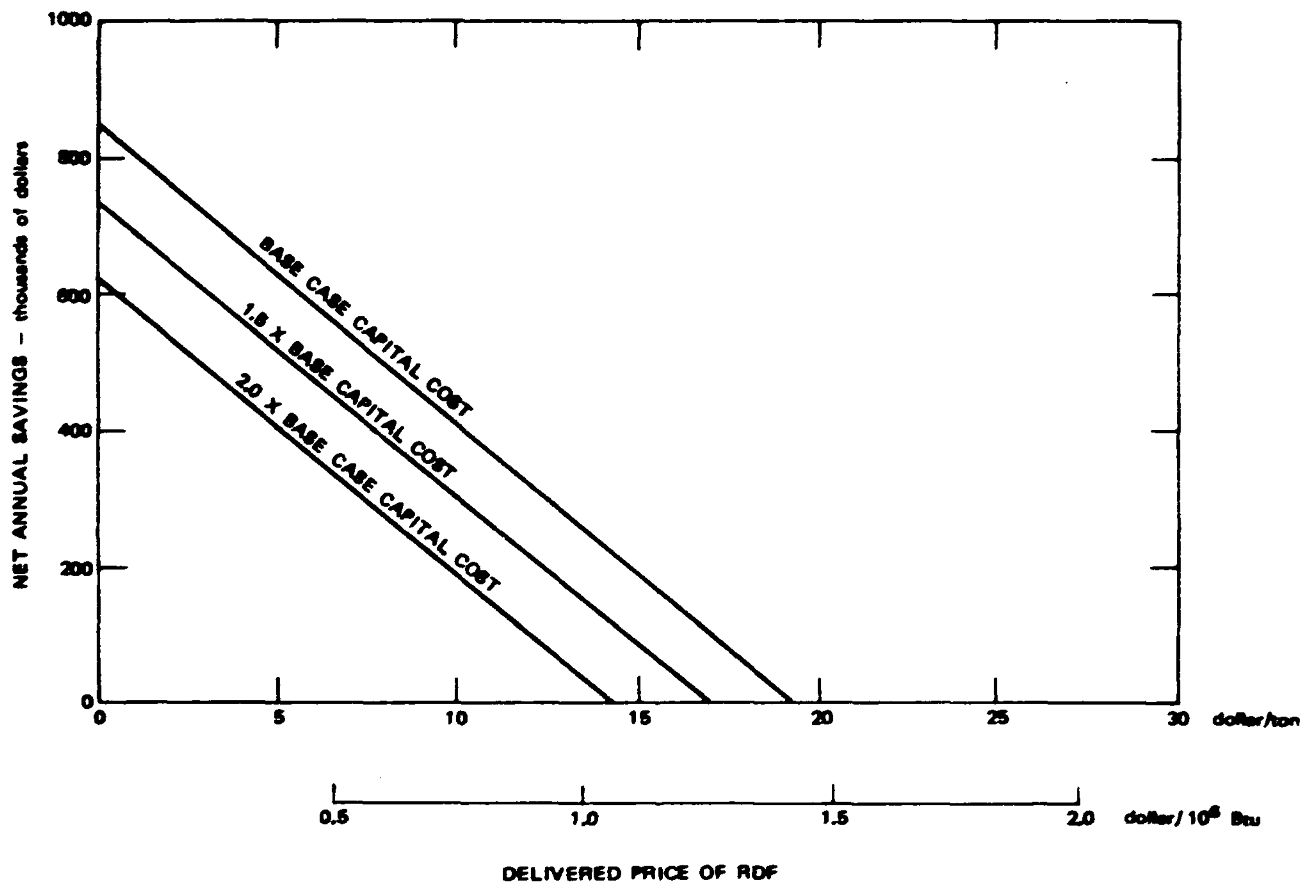


FIGURE 15. NET ANNUAL SAVINGS AS A FUNCTION OF DELIVERED PRICE OF RDF (Case Study)

- A study of possible design improvements for shop-fabricated incinerators to achieve more complete combustion of fixed carbon in ash and to achieve better process control.
- A continuing review and evaluation of developments in small-scale solid waste conversion units, including annual written reports on significant design improvement. (Auger bed incinerator development is a possible subject to be included, as are updates on gasification and pyrolysis units. European work on mechanical grate units is another possible topic.)
- A preliminary technical/economic evaluation of the O'Connor rotary combustor, including a site visit to the 50-ton/day plant reported to be operating in Yokohama, Japan.
- The circumstances encountered in the Case Study can only be representative of a "class" of Navy Base facilities. Similar studies should be conducted for other classes of installations to provide the Navy with a broader basis for determining their waste utilization potential and the corresponding capital and O&M requirements to accommodate waste fuel firing.
- A program for developing a special purpose, moderate-size steam generating unit designed specifically to accommodate Navy refuse in the as-discarded form. This type of unit would have broad application, singly or in multiples, at many Navy Base facilities.

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Appendix A

MASS BURNING OF REFUSE IN SHOP-FABRICATED INCINERATORS

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I INTRODUCTION

One available option for disposal of solid wastes from military bases is mass burning of unprocessed refuse in shop-fabricated incinerators. A number of military bases, including several Navy bases, have installed or plan to install shop-fabricated incineration units. The following review of available technology and generalized cost correlations has been prepared for inclusion in the SRI-developed data base to be used by Navy planners responsible for solid waste management and energy conservation.

A. Scope of Work

The precise scope of this task effort is summarized below:

- Prepare a comprehensive list of suppliers of shop-fabricated refuse incinerators that may be installed at plants with design capacities of less than 100 ton/day of refuse. Suppliers in North America as well as in Western Europe are to be included.
- Classify the suppliers as to (a) current production of units for mass burning of municipal refuse with heat recovery boilers (and possibly air pollution control devices), (b) active development of a unit for mass burning of refuse, and (c) production of units for other types of wastes or residues.
- Select several installations of units from suppliers in category (a) above for on-site inspections to gather data concerning operating costs, operation and maintenance practices, environmental control practices, and energy recovery programs.
- Prepare investment and operating cost estimates based on data gathered from site visits and contacts with unit suppliers. Costs are to be presented for several levels of pollution control and for a capacity range of from less than 10 ton/day to about 100 ton/day. All significant design assumptions and cost estimating bases will be noted.

B. Background

Unprocessed refuse may be incinerated in shop-fabricated combustion equipment or field-fabricated equipment. To date, the most widely used type of shop-fabricated units are horizontal flow, cylindrical furnaces with both a primary and a secondary combustion chamber. Such incinerators have not generally been available with single-unit capacities greater than 25-30 ton/day, primarily because the units must be shippable by truck. If larger capacities are required, facilities have been designed to have multiple units. For example, a 100-ton/day facility may have four 25-ton/day modules. New designs with single-unit capacities of up to 100 ton/day are now available.

Shop-fabricated incinerators have been used to burn municipal refuse in the United States only within the last decade. Heat recovery from such units has been practiced only within the last 5 years, although large, field-erected incinerators with heat recovery have been used for many years.

Once the facility capacity requirement is in the range of hundreds of tons per day, field-fabricated incinerators become economically attractive. Within the last several decades, most European field-erected incinerators have been large water-wall furnaces; the United States has used these units for the last decade. Before that time, the large field-erected incinerators were refractory chambers with temperature control, achieved in part by injection of large quantities of excess air. Heat recovery with the refractory wall units has not been wide- spread but is becoming more popular as energy costs escalate.

In water-wall furnaces, which are steam producers, unprocessed refuse is burned on inclined, mechanically actuated grates. Semisuspension burning,[a] however, is now being practiced with some units in Europe and is proposed for several sites in the United States.

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[a]Spreader stoker design.

Public Health Service, Bureau of Solid Waste Management, Ralph Stone and
Company. Inc., Engineers, Los Angeles, California (1969).

Semisuspension burning requires preprocessing (size reduction, ferrous metals removal, and separation of combustibles from noncombustibles). The units can also burn coal, which is an important factor in many locations. Units that are equipped with high-energy scrubbers, electrostatic precipitators, or fabric filters have proved able to meet stringent particulate emission standards. All large field-erected incinerators are designed to operate 24 hours a day for 5 to 7 days a week.

Because most Navy installations do not generate more than 50 ton/day of refuse, shop-fabricated units are the most appropriate type of incinerator in most cases, unless solid wastes from the surrounding area are also to be burned. Although numerous types of shop-fabricated incinerators exist, most fall within one general class: two-stage combustors with the first stage operating with substoichiometric air, and the second stage serving as an afterburner to burn gases and particulates. These two-stage units are commonly referred to as "controlled-air" or "starved-air" incinerators. The suppliers of these units claim that particulate emissions can be adequately controlled by the secondary combustion chamber and thus no particulate collection device is required. (This claim will be carefully evaluated in the technical evaluation of the units.)

The market for shop-fabricated incinerators has historically been comprised of industrial plants, commercial sites, and hospitals where the wastes are mainly composed of paper and plastic packaging materials, wood scraps and pallets, office paper, and food scraps. On the basis of reports by equipment suppliers, more than 5,000 of the controlled-air units have been installed in the United States within the last decade, but fewer than 100 of these installations practice heat recovery. Because most of these units burn waste materials with little ash content (relatively few bottles and metal cans), automatic ash removal equipment is not generally installed. Some units at industrial sites can operate three shifts a day, six days a week, with cleanout of ash scheduled during a shutdown on the seventh day.

CDC 6400 Extended FORTRAN

The CDC 6400 version of standard FORTRAN was used to sort data files held in the SIR system and to carry out arithmetic computations using the data. This FORTRAN language is a version of the common FORTRAN programming language that has been tailored for use on the CDC 6400. The sorting activities included the retrieval of data files and resequencing of the information on the basis of certain attributes identified in each data base. Specifically, data stored in a random sequence were ordered into two new files in sequence according to waste generator type in one file and acording to waste type in the other. FORTRAN programs were used to perform summations using the new sorted files, to calculate bulk load densities, and to prepare new files for input to SPSS.

SPSS

SPSS is a package containing subprograms to carry out a multitude of arithmetic, graphical, and statistical procedures. It is used to analyze data, test hypotheses, plot, and to do many other activities. In this report, SPSS was used to perform regression analyses for coefficient estimation and to test confidence levels of the coefficients generated.

Regression analysis is a technique used to generate the coefficients for an equation that can describe the relationship between a measured variable (like volumes of each waste type) and an unknown variable (the weight of a load consisting of a certain mix of waste types). In the regression analysis, the observations of the "independent" variables (e.g., volumes of waste types) and the "dependent" variable (i.e., weight of a load) are compared to determine coefficients that represent the relationship between the variables (here, the densities of each waste type).

II SURVEY OF TECHNOLOGY IN THE UNITED STATES AND WESTERN EUROPE

A. U.S. Technology

From listings of equipment suppliers in trade journals, discussions with suppliers at trade shows and conferences, and personal communication with consulting engineers concerned with combustion equipment, SRI has compiled information on shop-fabricated combustion equipment for solid wastes as well as for agricultural and forestry residues. Those suppliers that have installed shop-fabricated units to burn municipal refuse or that are attempting to sell units for that purpose are listed in Table A-1. The suppliers are classified into three major categories:

- Those with systems (including heat recovery) now burning municipal refuse.
- Those with units not now burning municipal solid waste (MSW) but with the potential to do so or with units burning MSW but without heat recovery.
- Those with units requiring extensive development to allow burning of municipal refuse or units not designed for heat recovery.

Table A-1 also notes any need for processing of the refuse before combustion. The table also indicates the type of furnace and hearth, the method of ash removal (manual or automatic; ash pusher or bomb-bay doors), the type of boiler usually supplied, the type (if any) of particulate collection equipment usually supplied, and the range of capacities available for individual modules.

Table A-2 identifies the sites (by supplier) where MSW is now or soon will be burned in shop-fabricated incinerators. Table A-3

Table A-1

SHOP FABRICATED INCINERATORS AVAILABLE IN THE UNITED STATES
TO BURN ≤ 100 TON/DAY OF MUNICIPAL REFUSE

[illegible]	Developer	Ash Removal	Heat Recovery	Air Pollution Control	Single Unit Size (ton/day)	Preparation Required	Comment
[illegible]							
[illegible]							
[illegible] refractory [illegible]	Consumat Incinerator* Consumat Systems Inc. P.O. Box 9379 Richmond, Virginia 23227	Ash pushers or batch	WTB	CAI	12-50	1	1 large installation undergoing shakedown
[illegible]	O'Connor Combustor Corp. 100 Kalmus Drive Irvine Industrial Complex Costa Mesa, CA 92626 (714) 979-3993	Continuous	WWF and WTB	ESP	20-200	1	1 unit operating in Japan
[illegible] with Heat Recovery							
[illegible]							
[illegible] refractory [illegible]	Comtro Division* Sunbeam Equipment Corp. Century Plaza Suite 510 Lansdale, PA 19446 (215) 699-4421	Ash pushers	FTB preferred WTB if required	CAI (can supply scrubber)	20-50	1	No municipal refuse with heat recovery
	Kelley Company, Inc 7620 North Teutonia Ave Milwaukee, WI 53209 (414) 352-1000	Batch or automatic		CAI	≤ 36	1,2	Municipal refuse experience but not heat recovery
	Environmental Control Products** P.O. Box 15753 Charlotte, NC 28210 (704) 588-1620	Ash pusher	FTB	CAI	5-30	1,2	Limited experience with municipal refuse
	Basic Engineering Inc.* 21 W 161 Hill Glen Ellyn, IL 60137 (312) 469-5340	Batch-bombay door (municipal would use pusher)	WWF and WTB	CAI	25-[illegible]	1	No municipal refuse experience No heat recovery experience
	Econotherm Energy Systems 11321 K-Tel Dr Minnetonka, MN 55343 (612) 938-3100	Batch-bombay door (municipal would use pusher)	FTB, WTB under development	CAI (can supply scrubber)	5-30	1	No municipal refuse experience
	Trecan Limited 4540 Dixie Road Mississauga, Ont. (416) 625-4030	Batch-2 unit for continuous operation	WTB	Scrubber	< 100	1	No heat recovery with municipal refuse

Table A-[illegible]. Continued

Design	Developer	Ash Removal	Heat Recovery	Air Pollution Control	Single Unit Size (ton/day)	Preparation Required	Comment
A. Stationary refractory hearth (continued)	George L. Simonds Co 909 Fifth St SW P.O. Box 32 Winter Haven FL 33880 (813) 293-2171	Batch	FTB	CAI		1	No municipal refuse experience
	Morse Boulger Inc 53-09 97th Place Corona NY 11368 (212) 699-5000	Continuous	FTB WTB	CAI CAI with scrubber	1-30	.	No municipal refuse experience in packaged incinerators
	Incinerator International 2702 N Main St P.O. Box 8617 Houston, TX 77009 (713) 227-1466						
B. Agitated bed	Scientific Energy Engineering						
C. Rotary kiln	Progressive Equipment Corp. 1330 Blue Hills Ave. Bloomfield CT 06002 (203) 242-0721	Continuous	FTB	CAI	1-24	1	No municipal refuse experience

*These producers are all moving toward the same basic design--stepdown hearths with a pusher on each hearth and long chambers to get good burndown.

*Municipal waste incinerators would be different from standard models offered--much longer primaries to achieve good burnout.

Preparation requirements:

1. Bulky removal
2. Glass and can removal

Abbreviations:

- FTB Fire Tube Waste Heat Boiler
- WTB Water Tube Waste Heat Boiler
- WWF Water Wall Furnace
- CAI Controlled Air Incinerator With Secondary Combustion Chamber
- ESP Electrostatic Precipitator

Table A-2

SELECTED INSTALLATIONS OF SHOP-FABRICATED INCINERATORS BURNING MUNICIPAL REFUSE (SINCE 1974)

Equipment Supplier	Site of Installation	Ash Removal	Designed with Heat Recovery	Air Pollution Control	Number of Units Installed	Total Facility Design Capacity+ (ton/day)	Operating Schedule (shift/day)§	Plant Startup
Comtro Division Sunbeam Equip. Corp. Lansdale, PA	Pelham, NH	Manual	No	CAI**	2	16	1	1977
	Jacksonville, FL (Navy)	Automatic	Yes	CAI	3	75	[illegible]	1978
Consumat Systems, Inc. Richmond, VA	Blytheville, AR	Manual	Yes	CAI	4	48	1	1975
	N. Little Rock, AR	Automatic	Yes	CAI	4	100	3	1977
	Orlando, FL	Manual	No	CAI	8	100	1	1974
	Pahokee, FL	Manual	No	CAI	2	17	1	1974
	Siloam Springs, AR	Manual	Yes	CAI	2	21	1	1975
	Pittsfield, NH	Manual	No	CAI	1	5-6	1	Planned for 1978 or 1979
	Auburn, ME	--	Yes	--	--	150	--	
	Dyersburg, TN	--	Yes	--	--	100	--	1980
	Genesee Township, MI	--	Yes	--	--	100	--	1979
	Salem, VA	--	Yes			100		1979
Environmental Control Products, Charlotte, NC	Diamond International Groveton, NH	Automatic	Yes	CAI	1	~20 ton/day	3 (Unit burns municipal refuse only 1 shift/week	1975
Kelley Company, Inc. Milwaukee, WI	Auburn, NH	Manual	No	CAI	1	5-6	1	1978
	Bridgewater, NH	Manual	No	CAI	1	5-6	1	1977
	Candia, NH	Manual	No	CAI	1	5-6	1	1976
	Canterbury, NH	Manual	No	CAI	1	3-4	1	1978
	Harpswell, ME	Manual	No	CAI	1	5-6	1	1978
	Kittery, ME	Manual	No	CAI	2	20-25	1	1978
	Meredith, NH	Manual	No	CAI	2	10-12	1	1977
	Nottingham, NH	Manual	No	CAI	1	3-4	1	1975
	Pittsfield, NH	Manual	No	CAI	1	5-6	1	1977
	Wolfeboro, NH	Manual	No	CAI	1	5-6	1	1977
	Sutton, NH	Manual	No	CAI	1	3-4	1	Planned 1979
	Lincoln/Woodstock, NH	Manual	No	CAI	1	5-6	1	Planned 1979
O'Connor Combustor Corporation Costa Mesa, CA	Gallatin, TN	Automatic	Yes	ESP	2	150	3	Planned 1980
	Dubuque, TN	Automatic	Yes	ESP	2	200	3	Planned 1980
Combustion Engineering* Windsor, CN	Numerous	Manual	No	CAI	--	--	--	Prior to 1975
Smokatrol	Crossville, TN		Yes			60		1979
CICO	Lewisburg, TN		Yes			60		1979

*Not currently active in the sale of this line of equipment.

+Based on operating schedule indicated in the adjacent column.

**Controlled air incinerator with secondary combustion chamber

§One shift may range from 6 to 10 hours of operation.

Note: For most equipment suppliers the foreign installations have not been listed.

lists the sites that were visited during this study to gather data on operating experiences. We visited the Basic Environmental Engineering unit in the Chicago area because we learned that their unit was being evaluated by the staff and consultants of St. John's University and Abbey (Collegeville, Minnesota), along with units supplied by the Comtro Division of Sunbeam Equipment Corporation, Consumat Systems, Inc., Econo-Therm, and the Kelley Company. We also visitied the Comtro unit at Knoll Furniture. No Comtro unit was burning MSW; several additional installations are under construction. The other sites were selected as representative of typical installations of specific suppliers as well as being within travel budget constraints. Inspection of the O'Connor unit at Yokohama (50 ton/day capacity) would be worthwhile, but such a trip was not within the scope of this effort.

Table A-3

SITES VISITED TO INSPECT SHOP-FABRICATED INCINERATORS

Equipment Supplier	Site of Installation
Basic Environmental Engineering	Dominick's Market Distribution Center[a] Chicago, Illinois
Comtro Division, Sunbeam Equipment Corporation	Knoll International[b] East Greenville, Pennsylvania
Consumat Systems, Inc.	North Little Rock, Arkansas Blytheville, Arkansas
Environmental Control Products	Diamond International Groveton, New Hampshire
Kelley Company, Inc.	Meredith, New Hampshire Pittsfield, New Hampshire

[a]Burns packaging material and some food wastes.

[b]Burns wood waste and plant trash.

Although some companies have installed units with gas-to-gas heat exchangers to recover heat for building heating systems, only steam generation was considered in this study because of the more widespread need for steam on a year-around basis at Navy installations.

The findings from the site visits and discussions with the equipment vendors and operators are summarized in a later section of the report.

B. Other U.S. Technology Identified But Not Evaluated

Fluidized bed combustion of processed MSW has been the subject of research for the last decade. Much of the research work has been conducted by the Combustion Power Company of Menlo Park, California, under EPA sponsorship. A fluidized bed has also been tested for combustion of the short fiber stream at the Black-Clawson Resource Recovery plant at Franklin, Ohio. Sewage sludge was burned along with the short fiber stream. A codisposal facility for sewage sludge and processed MSW that will use a fluidized bed combustor is being installed at Duluth, Minnesota. A fluidized bed combustor with a heat transfer surface in the combustor is currently being evaluated by Stanford University and Combustion Power Company under EPA sponsorship for MSW combustion.

In fluidized bed combustors, however, the MSW must be shredded and the heavy fraction (metals, glass, other inorganic solids) removed before combustion. For a small facility, extensive preprocessing is not economically feasible. One leading company in this field[a] is now evaluating the possibility of using a trommel screen alone for

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[a]Energy Products of Idaho has been supplying fluidized bed combustors to the forest products industry since 1972. During the 4-year period from 1973-1977, the company installed 22 commercial units in sizes up to 80×10^6 Btu/hr.

processing MSW injected into the combustor. Energy Products of Idaho believes that its combustor may offer an attractive option for communities needing to burn less than 200 ton/day of refuse. Testing of the concept is under way now at the company's pilot plant in Idaho.

Another current development effort that Navy personnel are aware of is the auger-bed incinerator. Hoskinson and Associates, the developers, conducted a field demonstration of this unit during May 1977. The results of the field evaluation have been reported by the Army Construction Engineering Research Laboratory.[a] The field study "demonstrated short-term successful operation" with the auger-bed incinerator "processing up to 3.5 tons/hour of solid waste--more than three times the throughput capability of currently marketed modular solid-waste incinerators." Because of certain design problems, the unit is not considered commercial at this time. The concept, however, does appear to have technical merit.

C. Western European Technology

Professor A. G. Buekens and J. G. Schoeters surveyed Western European incineration technology. Table A-4 summarizes the characteristics of shop-fabricated units that they identified as being suitable for incineration of 20 to 100 ton/day of MSW. European companies do not appear to have much experience with shop-fabricated municipal incinerators that burn MSW, but numerous companies with units that burn plant trash have offered to build such units. Buekens and Schoeters did not identify any existing modular unit that is burning MSW. Many suppliers of large incinerators have offered to build small capacity field-erected units for MSW that are adapted or scaled down from their larger

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[a]S.A. Hathaway, J. S. Lin, and A. N. Collishaw, "Field Evaluation of the Modular Auger-Bed Heat Recovery Solid Waste Incinerator," U.S. Army Corps of Engineers, Technical Report E-128 (May 1978).

Table A-4

SHOP-FABRICATED INCINERATORS AVAILABLE IN EUROPE TO BURN
$\leq$ 100 Ton/Day of Municipal Refuse

Supplier	Design	Air Pollution Control	Comments
Almeco S.A. (Italy) Tecnital (Belgian sales representative)	Fixed or moving grate	Controlled air (additional control can be supplied)	No apparent experience with municipal refuse
Redman Heenan Froude Ltd. (England)	Fixed refractory hearth	Unknown	No experience with heat recovery
Hoval-Werk A.G. (Liechtenstein)	Fixed refractory hearth	Controlled air	Kelley-Hoskinson design. Only controlled air unit with a strong market position
OY Tampella A.B. (Finland)	Rotating conical grate	Cyclone and/or scrubber	No units operating on municipal refuse
Trummer (Switzerland)	Transporting step grate	Patented device	
Compagnie des Fours D'Incineration-- S. A. Muller (France)	Fixed refractory hearth		
Elbona (Belgium)	FreeCALOR a) fixed step grate b) Rotating conical grate	Multi-cyclones	Primarily wood wastes One refuse unit not trouble free
LAMBION (Germany)	Reciprocating grate, probably field erected	Multi-cyclone	Designed as bark burner
Cornel Schmidt Eisen und Stahlwerk GmbH (Germany)	Avomat a) reciprocating grate b) rotating grate (shredded refuse)	Multi-cyclone	
Vyncke pvba (Belgium)	Screw underfeed stoker	Multi-cyclone	Requires shredding. Designed for low ash material
Plibrico (Netherlands)	Ceramic or continuous belt grate controlled air	Multi-cyclone or precipitator	Makes packaged incinerators and large field erected units
W.S.I. b.v. (Netherlands)	Inclined stationary grate	Controlled air	Designed as wood waste burner

designs. Therefore, most incinerators with a capacity of 20 to 100 ton/dav do not use the stationary horizontal refractory hearth that is used almost exclusively in the United States. Instead, most incinerators use some version of a mechanical grate--either rocking, transporting, or rotating. Most suppliers include an air pollution control device such as a scrubber or multicyclone.

At this time, European technology in building shop-fabricated incinerators does not appear to be superior to U.S. technology. Because small capacity units in Europe use mechanical grates, the units are relatively expensive. In the future, more information should be obtained from European companies on small field-fabricated units burning MSW to determine the costs and whether they are less prone to slag problems or provide more complete burndown than U.S. units.

III TECHNICAL EVALUATION OF OPERATING UNITS IN THE UNITED STATES

A. Incinerators with Capacities of More Than 20 ton/day

Four installations of shop-fabricated incinerators were visited:

- o A Consumat installation at Blytheville, Arkansas
- o A Consumat installation at North Little Rock, Arkansas
- o A Basic installation at a Dominick's Market warehouse in Chicago, Illinois
- o A Comptro installation at Knoll Furniture, East Greenville, Pennsylvania.

On the basis of these site visits, some general comments on the state of the art of municipal refuse incinerators are possible.

1. Construction Quality and Unit Lifetime

Current construction standards are probably inadequate for long-term use by municipal personnel. Some units, for example, have loading facilities that do not appear to be designed to be sturdy or to have sufficient safety interlocks. As a result, the door that closes the top of the loading hopper during the feeding cycle warps. The lack of insulation of some units made working near them uncomfortably hot; high temperatures were particularly noticeable near heat recovery units. Some access doors to the incinerators and heat rec[illegible]quip-ment did not have heavy-duty hinges, a particularly bad [illegible] these units require frequent (several times daily) visua[illegible]

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1. Construction Quality and Unit Lifetime

Current construction standards are probably inadequate for long-term use by municipal personnel. Some units, for example, have loading facilities that do not appear to be designed to be sturdy or to have sufficient safety interlocks. As a result, the door that closes the top of the loading hopper during the feeding cycle warps. The lack of insulation of some units made working near them uncomfortably hot; high temperatures were particularly noticeable near heat recovery units. Some access doors to the incinerators and heat recovery equipment did not have heavy-duty hinges, a particularly bad defect because these units require frequent (several times daily) visual inspection.

From the limited data available, unit lifetime is difficult to estimate. Consumat promises 25 years, which is probably unrealistic, given the condition of some in-service units. The Blytheville unit, which has been operating for only 3 years, shows significant deterioration. The inside walls of the primary combustion chamber are almost worn to bare metal in a few small places, and the metal and paint on the outer surfaces are discolored--a sign of severe overheating. Oxidation has made holes in the metal shell in some places, which have been patched with welded-on metal pieces. Two of the four units at Blytheville will probably be replaced within the next year. Some damage is probably due to operation above design capacity and inadequate maintenance--the Blytheville plant has had several plant managers and budget cuts since it was built--but the units should have been constructed to deal with this.

Because some of the design errors leading to the rapid deterioration of the Blytheville unit have been corrected, North Little Rock, which was the next major Consumat installation, will last longer. However, the jump to a 25-year lifetime probably cannot be made in one cycle of design changes, especially when the new units look so much like the old ones. External signs of overheating are already visible.

The Comptro and Basic units look as though they hold up better, but they are not in municipal service and have only been operating for a few years. More time will be required to determine their service life.

2. Temperature Control

Temperatures can be controlled in shop-fabricated incinerators in a number of ways. The primary chamber operates with substoichiometric air so that in response to short-term temperature changes its temperature can be raised by increasing air rates or, in the case of a fixed air supply, by adding refuse at a lower rate. Alternatively, the primary temperature can be lowered by decreasing the air rate or by adding more

refuse without changing the air rate. As an emergency measure, the primary temperature can be lowered by adding water from a spray system.

The secondary combustion chamber operates with excess air so that in response to temperature changes it can be cooled by adding more air, or heated by burning auxiliary fuel. (Heating by using less air is probably not wise because this might interfere with providing complete combustion). An additional temperature control option is to cool the secondary combustion chamber by adding less air to the primary chamber; this would reduce the amount of gaseous fuel volatilized from the refuse and therefore decrease the amount of fuel fed to the secondary chamber.

A strong interaction exists between the temperature in the secondary chamber and any measures used to control temperature in the primary chamber. For example, if the primary chamber is cooled by adding more refuse, the secondary chamber temperature will tend to rise because of the rapid devolatilization of the refuse and the subsequent increase in the fuel-to-air ratio in the secondary chamber. The temperature rise can be dampened by increasing the secondary air flow, but this strategy will decrease residence times in the secondary chamber and may cause air pollution.

Most of the shop-fabricated incinerators visited had simple temperature control systems and required a high level of operator skill. Temperatures could not be completely controlled by simply adjusting air flows. Some systems had locking devices to prevent overfeeding, but none could indicate when faster feeding rates were necessary. At all installations, the temperatures in the incinerators and the condition of the burning refuse were not visible to the operator responsible for loading. An inspection of small temperature gauges and the incinerator (the primary chamber requiring a visit outside the loading area and manual opening of an access door) had to be made by supervisory personnel. The supervisor's experience then served as the basis for his verbal communication to the operator regarding the loading strategy until the

next inspection. For example, at the Consumat installation in North Little Rock, the primary chamber in one unit overheated during the lunch hour because the operator did not feed it for a half hour. The overheating was detected by the supervisor, who turned on the water spray and instructed the operator to feed the unit rapidly to bring the primary temperature down. These two control measures caused the unit to smoke badly.

Of all the sites visited, the Basic incinerator, which burns mostly cardboard, had the most sophisticated control system. Basic uses modulated air as the primary temperature control and a lockout to prevent overfeeding. Once the unit was operating within the desired temperature range, only a minimum of auxiliary fuel was required to maintain the proper temperature in the secondary chamber.

3. Heat Recovery Boilers

Comptro has no heat recovery boilers in MSW service that could be inspected. Basic has not yet installed a heat recovery boiler. Both Basic and Comptro indicate that fire tube boilers would work well in this service and that soot blowing can be made automatic. Consumat supplies water tube boilers, but the original design, represented by Blytheville, appears to have been inadequate. The boilers are no longer operational because they are too compact, cannot be kept soot-free, and corroded badly. Almost all tube fins are gone. However, the new units at North Little Rock seem to be better designed. Individual tube banks can be replaced and enough space inside the unit exists to provide adequate soot blowing. At present, the first bank of tubes cannot be cleaned automatically, but modifications to solve this problem are under way. Whether all problems have been solved is not yet known. The units, which have been operating for less than a year, are still undergoing shakedown and have not been able to meet their steam commitments on a sustained basis, As a result boiler efficiency cannot be assessed.

4. Burndown

During the site visits, only the two Consumat units were burning MSW. The unit at Blytheville, which did not have automatic ash removal, was discharging an almost completely inorganic ash. The units at North Little Rock (operating three shifts a day with continuous ash removal) were not providing complete burndown during our visit. Magazine pages were readable in the ash stream, and grass clumps were still green inside. This occurred even though the units were being fed at only 90% of their design capacity. Apparently, additional development (possibly added residence time or changes in the underfire air system or both) is required for the continuously operated units. Any fixed hearth unit supplied by vendors other than Consumat will most likely have the same problems because they all have similar designs.

The two municipal units visited produce some slag, but the slag does not apparently attack the refractory or otherwise significantly affect operation. The Consumat design for North Little Rock did have trouble with slag clogging the underfire air ports, but this has been fixed by a field modification.

5. Air Pollution

None of the sites visited included auxiliary controls for air pollution control. The two incinerators burning plant trash showed no plume during normal operation, primarily because they both burn a lowash material and therefore do not use ash-moving rams during the burning period. Moving the ash stirs up particulates.

The two Consumat units showed visible plumes during operation and occasionally visible pieces of ash. The North Little Rock units had automatic soot blowing, which released a 10- to 20-second plume of brown smoke every time it operated. Units with continuous ash removal will

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probably require an auxiliary device to operate in compliance with air pollution regulations, especially if complete burndown of fixed carbon is required.

B. Small Refuse Incinerator Sites (Less Than 20 ton/day)

Several small incinerators were visited, including:

- o Kelley Incinerator, Meredith, New Hampshire
- o Environmental Control Products Incinerator, Groveton, New Hampshire
- o Kelley Incinerator, Pittsfield, New Hampshire.

In general, the temperature control systems were simple and required skilled manual intervention. The stack condition and incinerator burning condition were not observable by the loading operators. Nor was temperature information readily available to the operator. A significant problem seems to be slag attack on the refractory; the slag was pulling pieces of refractory off the walls of the primary chamber. A jack hammer was used to remove slag from the Groveton unit. Source separation to remove glass is required at both Meredith and Groveton.

C. Air Pollution Control

1. Emission Standards

A number of air pollution control agencies were contacted during the study to determine what kinds of standards will apply to refuse burning in plants with a total capacity of less than 100 ton/day. The findings of our telephone survey for areas where there are large Navy installations are summarized in Table A-5. Currently, only particulate emissions (visible and mass emissions) are being regulated. In general,

Table A-5

SUMMARY OF SELECTED REFUSE INCINERATOR EMISSION STANDARDS

Area	Capacity of Incinerator	Visible Emissions	Mass Emiss'ons*
Puget Sound Area of Washington	All	Less than Ringelmann #1 (20% density); for 57 min/hr 3 min/hr (no limit)	0.10 grain/scf (corrected to 12% CO_2 exclusive of CO_2 from auxiliary fuel)
City of Phila-delphia, PA	All	Less than 30% density on Ringleman scale for 59.5 min/hr; 30 sec/hr or 3 min/day less than 60% density	0.08 grain/scf (corrected to 12% CO_2)
State of Florida	<50 ton/day	Zero visible emissions except for 3 min/hr when emissions are not to exceed 20% density on Ringlemann scale	
	>50 ton/day		0.08 grain/scf (corrected to 12% CO_2)
San Francisco Bay Area in California	<50 ton/day	Less than Ringlemann #1 (20% density) for 57 min/hr, 3 min/hr (no limit)	0.15 grain/scf (corrected to 6% O_2 with no auxiliary fuel)
(Comparable to standards in Los Angeles area)	>50 ton/day		0.08 grain/scf (corrected to 12% CO_2)
New Hampshire	>200 lb/hr	--	0.2 grain/scf (corrected to 12% CO_2)
	>50 ton/day	--	0.08 grain/scf (corrected to 12% CO_2)
Hawaii	<50 ton/day	--	--
	>50 ton/day	--	0.08 grain/scf (Corrected to 12% CO_2)

*Dry gas basis in all cases.

all regions have mass emission standards for particulate matter comparable to the EPA New Source Performance Standards (NSPS) of 0.08 grains per dry standard cubic foot (dscf), corrected to 12% CO_2 for units with a capacity to burn more than 50 ton/day of refuse.

Mass emission requirements for smaller units range from the same as NSPS for larger units, to 0.2 grains/dscf (corrected to 12% CO_2). No regulations directly address the issue of soot blowing the heat recovery boilers. Several individuals contacted felt that incinerators with heat recovery boilers may be required to comply with standards for solid waste or residue-fired boilers. These standards are not necessarily more stringent than those for incinerators. In Florida, for example, units with less than 30 x 10^6 Btu/hr of input must have visible emissions of less than 20% density on the Ringelmann scale, except for 2 minutes per hour, where a density of 40% is allowed. This is more lenient than the standard in Florida for an incinerator with a capacity of less than 50 ton/day, (30 x 10^6 Btu/hr would be equivalent to around 3.3 tons of refuse per hour, or close to 80 ton/day).

No standards now exist for control of chlorides and none have been proposed or are anticipated in the regions identified in Table A-5.

In noncompliance or nonattainment areas, criteria pollutants that exceed ambient air quality standards will be strictly regulated. If emission of a problem criteria pollutant from a new source exceeds 25 lb/hr or 250 lb/day, a new source review is required. "Offsets" may be necessary to allow installation of a new unit. On-site reductions in emissions from other sources will be accepted on a 1/1 basis in terms of mass. Off-site reductions will be considered on a case-by-case basis, but will not be on a 1/1 basis.

2. Compliance Monitoring

To date, few shop-fabricated units have been field tested while burning MSW. The State of New Hampshire conducted tests at Meredith on two Kelley units without heat recovery that are burning as many as 90 tons/week of MSW. The test results were as follows:

	Particulate Loading (grains/dscf corrected to 12% CO_2)	
First testing period (average)	0.213	
Second testing period (some burner modifications)	0.11 0.168 0.211	(Average meets NH standard of 0.2.)

Two other manufacturer's units are being installed in New Hampshire and will be tested in the future.

Under EPA and Navy sponsorship, Systems Technology Corporation (Systec) has been testing the Consumat units at North Little Rock, Arkansas. Their preliminary results (subject to change) were as follows:

Particulates: 0.038 grains/dscf (at 2.5% CO_2)
Range: 0.030 to 0.044
Approximately 0.18 grains/dscf (calculated based on 12% CO_2 content in the gas stream)

NO_x: 0.4 lb/10^6 Btu of input
Range: 0.34 to 0.46

CO: Approximately 30 ppm (at 2.5% CO_2)

Tests were conducted without the soot blowers operating. The concentration of CO_2 measured in the stack gas appeared to be too low. At 100% excess air, the CO_2 should be close to 8%. Some dilution is expected because Consumat uses an ejector to induce the draft through the boiler. However, the amount of excess air required to dilute the CO_2 to 2.5% seems excessive. The issue will be resolved when Systec's final results are made public.

A. Limitations on Use of Output

The investment cost estimates presented in this appendix are based on specific design assumptions, which are not likely to be applicable in all cases because of possible site-specific differences in solid waste composition, site conditions (need for pilings, possible use of existing structures or equipment, space limitations), and local construction labor rates and productivity. Price differences will also exist among vendors of specific types of equipment. In estimating operating costs, we could not select unit costs or rates for utilities and labor requirements that are appropriate for every site. Maintenance materials and labor are also difficult to predict. Therefore, the cost correlations should be used only for very preliminary evaluation to screen alternatives. The cost data should not be used as the sole basis for final selection of any one solid waste management option.

B. Mass and Energy Balances

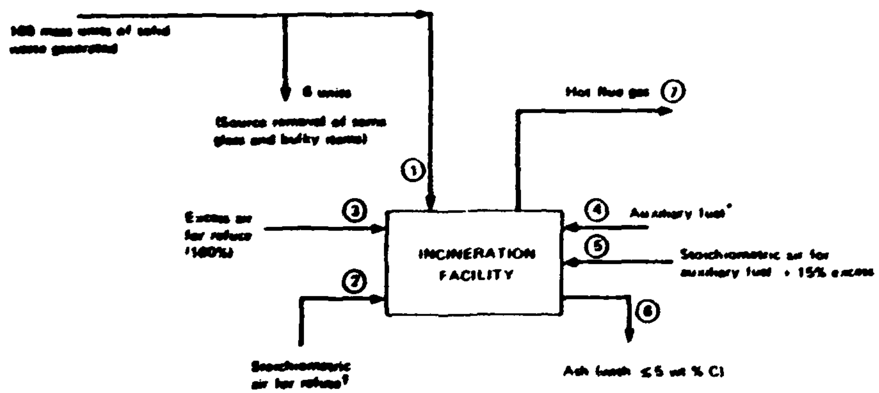
Table A-6 shows an estimated Navy refuse composition. A more complete analysis might show a different composition, but the changes would not substantially affect the technical and economic analysis of incineration.

On the basis of the refuse composition shown in Table A-6, mass and energy balances have been prepared (see Figures A-1 and A-2). We assume that glass and bulky wastes are removed before collection. Glass is separated to prevent clinker formation in the incinerator. In Figure A-2, 100 mass units of total refuse are used as a basis for the mass balance. The heating value of 1 ton of incinerator feed was calculated to be 10.1×10^6 Btu/ton.

Table A-6

TYPICAL COMPOSITION OF SOLID WASTE
FROM A NAVAL INSTALLATION
(by Waste Type)

Type of Waste	Wt.% (as received)
Paper	20
Cardboard	16
Mixed office waste	13
Wood	7
Yard waste	5
Food waste	21
Metals	5
Sludge	2
Glass	4
Other (Including bulky items)	7
	100



INCINERATOR MATERIAL BALANCE

Input = 1 + 2 + 3 + 4 + 5 = 855.8

Output = 6 + 7 = 855.4

	Streams						
Organic Material	1	2	3	4	5	6	7
C	29.4	--	--	1.09	--	1.5	--
H	4.0	--	--	0.17	--	--	--
O	26.0	--	--	--	--	--	--
S	0.15	--	--	0.008	--	--	--
N	0.35	--	--	0.001	--	--	--
Inorganic Material	9					9	
H_2O	25	1.6		--	0.1	--	65.7
O_2	--	85.8	85.8	--	5.0	--	90.7
N_2	--	282.2	282.2	--	16.2	--	580.9
CO_2	--	--	--	--	--	--	107.0
SO_2	--	--	--	--	--	--	0.3
NO_2‡	--	--	--	--	--	--	0.35
CO	--	--	--	--	--	--	Trace
Total	94	369.6	369.6	1.27	21.3	10.50	844.95

*No. 2 fuel oil at 0.6% S; ~19,722 Btu/lb

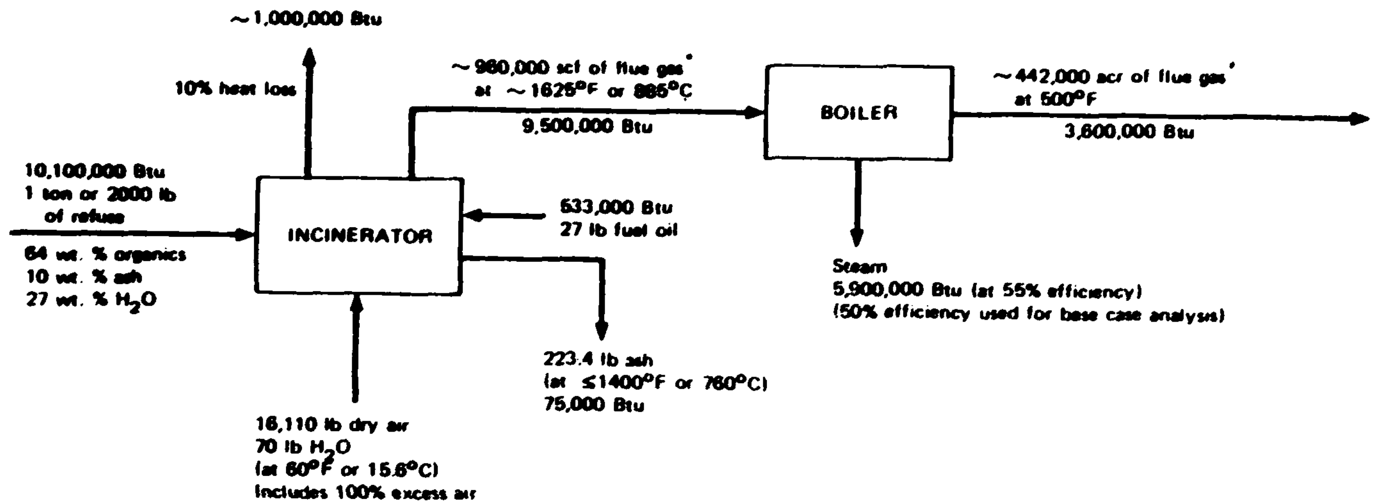
or 10,950 kcal/kg;

5% of fuel input from auxiliary fuel

†Inlet air at 60°F or 15.6°C with 40% relative humidity

‡Calculated on the basis that ≤ 30% of organically bound nitrogen converted to NO_2 and insignificant amount of NO_2 formed from oxidation of N_2 in air

FIGURE A-1. MASS BALANCE FOR INCINERATOR PER 100 MASS UNITS OF SOLID WASTE GENERATED



Mass balance closes within 0.4%
Energy balance closes within 0.5%
Thermal efficiency = 55% at 10% heat loss
~50% at 15% heat loss ← Base case assumption for economic analysis
~45% at 20% heat loss

FLUE GAS COMPONENT	MASS (lb/ton refuse)	VOLUME (%)
H_2O	1,398	12.3
O_2	1,930	9.5
N_2	12,360	69.9
CO_2	2,277	8.2
SO_2	~6.4**	.....
NO_2	≤7.45**	.....
CO	0.02**	.....
Particulate	~3.5	.....

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* ~243,000 scf or ~213,000 dscf

** SO_2 equivalent to ~0.60 lb/10^6 Btu input
NO_2 equivalent to ≤0.70 lb/10^6 Btu input
CO ~100 ppm_v

† Equivalent to 0.12 grains/dscf or 0.18 grains/dscf corrected to 12% CO_2

FIGURE A-2. MASS AND ENERGY BALANCE PER TON OF INPUT TO THE INCINERATOR

The overall thermal efficiency is 50%, with 100% excess air input and a system equipment heat loss of 15%. The particulate emissions and CO emissions have been estimated on the basis of data for a Consumat unit burning MSW at North Little Rock, Arkansas; the data were supplied to SRI by Systec of Xenia, Ohio (another Navy contractor). The SO_2 emissions have been calculated on the basis of an assumed sulfur content typical of MSW. The NO_2 emissions are calculated on the assumption that less than 30% of the organic nitrogen content of the MSW is converted to NO_2 and that insignificant amounts of NO_2 are formed from oxidation of N_2 because of the low operating temperatures.

C. Specification of Plant Design Capacity

In the design of a facility capable of processing the MSW delivered from a 5-day/week collection operation, the assumed source separation of glass and bulky items, downtime for maintenance and holidays, and the probability that the unit cannot perform at all times at the rated mass-burning capacity must be considered. Taking these factors into account, the incineration operation must burn a tonnage of material 18% greater than the total tonnage of material generated on a 5-day/week basis (see Table A-7).

To include examples that are relevant to Navy operations, plant design capacities ranging from 7 to 100 ton/day have been specified for the economic analysis. Few Navy bases generate 50 or more ton/day of refuse, and most generate around 20 ton/day.

D. Economic Bases

Table A-8 summarizes information concerning the quantity of refuse burned per year for the four facilities considered and the number of shifts per day the facilities would operate. (The reason for selecting fewer hours of operation for the smaller facilities is discussed later in the analysis.)

Table A-7

CALCULATION OF DESIGN CAPAC TY FOR SAMPLE CASES

Refuse generation rate = X ton/day (5 days/week)
Refuse for burning = 0.94X (6% removed as glass and bulky items at source)

Incineration facility scheduled to operate 5 days/week for an average of 46 weeks/year (230 operating days/year, 10 holidays, 10 days of other downtime). Units will operate at 90% of rated capacity.

$$\text{Plant design capacity} = \frac{0.94X}{0.90} \; \frac{260 \text{ days available}}{230 \text{ days of operation}} = 1.18X$$

Refuse Generation Rates (tons/day)	Plant Design Capacities (tons/day)
Approx. 6	7
17	20
42	50
85	100

Table A-8

INCINERATION PLANT CAPACITIES CONSIDERED FOR ECONOMIC ANALYSIS

Approximate Quantity of Refuse Generated[a] (tons/day)	Plant Design Capacity[b] (tons/day)	Quantity of Refuse Burned (tons/day)[c]	(tons/year)	No. of Shifts Operated (shifts/day)
6	7	6.3	1,499	1
17	20	18	4,140	2
42	50	45	10,350	3
85	100	90	20,700	3

[a]Quantity generated 260 days/year (5 days/week, 52 weeks/year).

[b]Plant operates at 90% of design capacity.

[c]Quantity burned during each of the 230 days in a year that the unit operates.

Table A-9 summarizes the assumptions concerning the discount rate, economic life of structures and equipment, maintenance costs, ash disposal unit costs, utility prices, and labor rates.

E. Investment and Operating Cost Estimates

SRI has estimated the plant facilities investment costs, on the basis of data supplied by equipment suppliers, as well as on a review of actual costs for construction of a number of facilities. Cost estimates prepared by Pfeifer and Schultz/HDR, Inc., of Minneapolis, in a report prepared for St. John's University and Abbey in early 1978 were also reviewed.

The investment costs for facilities with design capacities from 2.5 to 20 ton/day are shown in Figure A-3. Note that no particulate collection devices are included. Costs are shown for facilities both with and without heat recovery (low-pressure steam production).

Table A-10 summarizes actual operating requirements for the incineration facilities. As an example of how operating costs have been estimated and the significance of labor charges, a facility with a design capacity of 20 ton/day will be discussed. Four cases will be considered for facilities operating 5 days per week:

A. No heat recovery/1-shift operation
B. No heat recovery/2-shift operation
C. Heat recovery/1-shift operation
D. Heat recovery/2-shift operation

Table A-11 shows the initial investment cost for the facility and the current value of the facility, taking into account replacement of the shop-fabricated incinerators after 12.5 years, or midway through the facility lifetime. Table A-12 describes the individual operating cost items. Note that labor charges represent from approximately one-half to two-thirds of the total operating costs (including capital charges) for the four cases considered at the 20 ton/day capacity level. In Table A-13, the quantities of steam produced for Cases C and D are shown, as

Table A-9

ECONOMIC BASES[a]

<u>Economic Life</u>	<u>Years</u>
Permanent buildings	25
Incinerator system	12.5
Heat recovery boilers	25
Air pollution control devices	25
<u>Ash Disposal Cost</u>	\$10.75/dry ton (in landfill)
<u>Maintenance Material Cost</u> (includes refractory replacement after 6.25 years of operation)	2.5% of total plant investment[b]
<u>Purchased Utility Costs</u>	
Water	\$0.60/1,000 gal
Electric power	3.0¢/kWh
Fuel oil	\$2.50/million Btu (around 36¢/gal)
<u>Labor Costs</u>	
Operating	\$6.0/hr[c]
Supervisory	20% of operating labor
Maintenance	2.5% of total plant investment
Administrative and support	20% of operating, supervisory, and maintenance
Payroll burden	30% of total direct labor costs.

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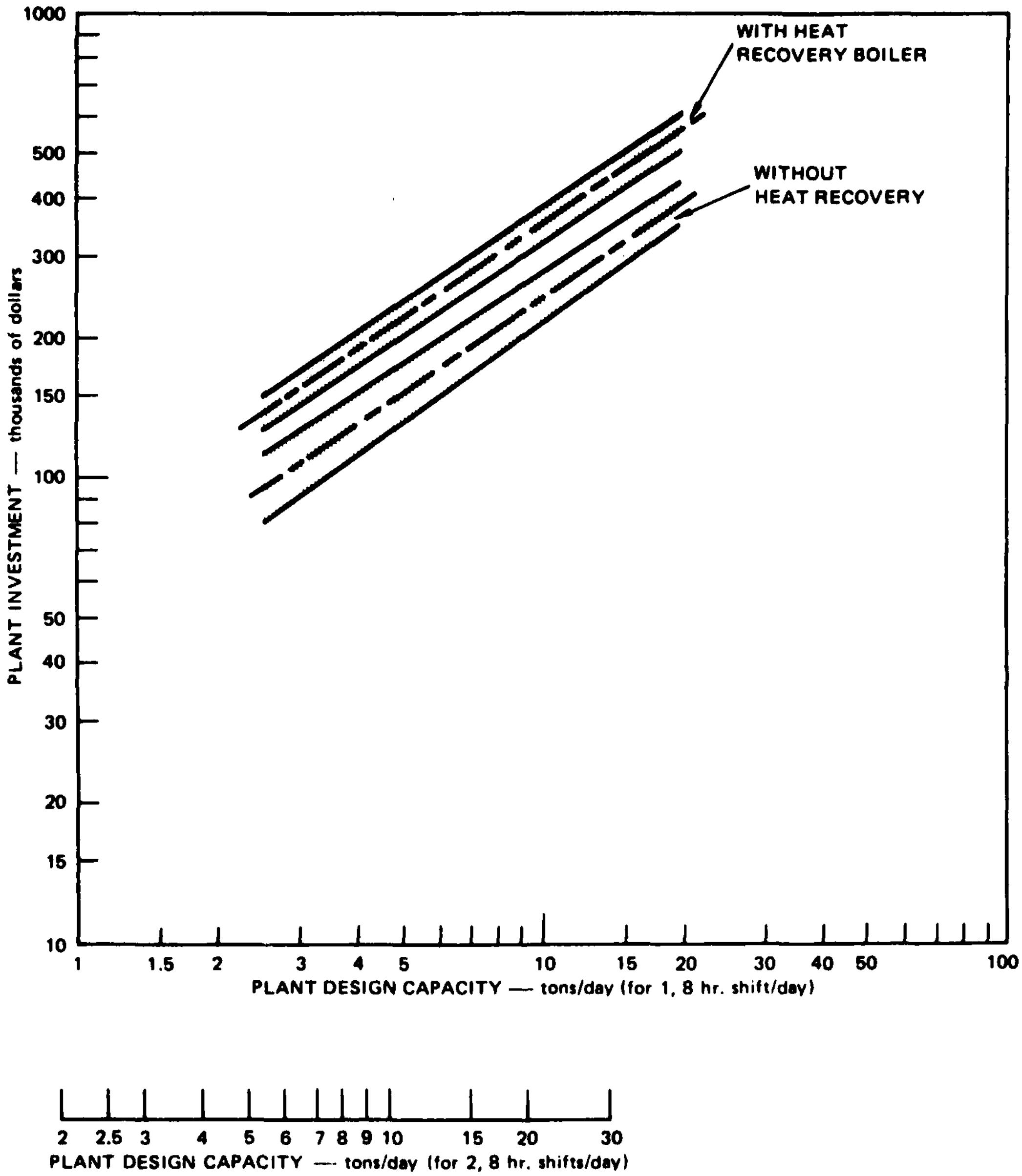
[a]Mid-1978 costs; discount rate = 10%.

[b]Unless noted otherwise.

[c]Gross earnings of nonsupervisory workers employed by public utilities supplying water, steam, or sanitary services, April 1978. Source: <u>Employment and Earnings</u>, U.S. Department of Labor Statistics, Vol. 25, No. 6, June 1978.



NOTE: No particulate collection device.

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FIGURE A-3 INCINCERATION PLANT INVESTMENT COST (< 20 ton/day capacity) AS A FUNCTION OF PLANT DESIGN CAPACITY (based on 1 shift and 2 shift per day operation)

Table A-10

SUMMARY OF PLANT OPERATING REQUIREMENTS

Item	Required
Auxiliary fuel	0.5×10^6 Btu/ton of refuse burned (around 5% of refuse heating value)
Electric power	10 kWh/ton refuse (No HRB, no PCD)[a]
	20 kWh/ton refuse (HRB, no PCD)
	30 kWh/ton refuse (HRB, PCD)
Operating labor[b]	2 men/shift (all plant sizes), around 100 ton/day
Ash disposal	0.1117 dry tons ash per ton refuse burned.

[a]HRB = heat recovery boiler
PCD = particulate collection device

[b]Multiply by 1.12 to take into account replacements for sick leave, vacation, personal leave, and overtime compensation. Supervisory, clerical, and maintenance labor requirements are estimated as separate items.

Table A-11

ESTIMATED INVESTMENT COSTS FOR HYPOTHETICAL REFUSE INCINERATION SYSTEMS

(20 ton/day Design Capacity, 4,140 ton/year Burned)

Case[a]	Approximate Incinerator Capacity (ton/hr)	Estimated Investment Costs Year 0	Year 13[b]	Present Value[c]
A	2.9	$385,000	$192,500	$440,767
B	1.3	230,000	120.000	264,764
C	2.9	550,000	183,333	603,111
D	1.3	325,000	108,333	356,384

[a]Cases with no heat recovery and no particulate collection (Case A, 1-shift; Case B, 2-shift).

Cases with heat recovery and no particulate collection (Case C, 1-shift; Case D, 2-shift).

[b]Replacement of shop-fabricated incinerators.

[c]At i = 10%.

well as the quantity from a 7-ton/day plant. Table A-14 itemizes the estimated operating costs for the 7-ton/day facilities, one with and one without heat recovery.

Without heat recovery included in a 20-ton/day plant, it appears from the data presented in Table A-12 that a one-shift per day operation would be preferable to a two-shift per day operation. Figure A-4 shows that for a plant with heat recovery, the decision between choosing a one or two-shift operation is influenced by the value of the steam produced. If the steam has a value of more than $\$2/10^6$ Btu,[a] the 2-shift operation is more attractive. Almost 25% more steam can be produced from a two-shift operation than from a one-shift operation (see Table A-13.)

For a 7-ton/day plant, Figure A-5 shows that steam must have a value of $\$3/10^6$ Btu for the heat recovery system to be economically attractive relative to the unit without heat recovery.

At the 50- and 100-ton/day capacity levels, the incinerator modules (25-ton/day each) will be designed with automatic ash removal and will operate 3 shifts per day for 5 days per week. In Table A-15, the estimated operating cost items are listed for plants both with and without fabric filters for particulate collection. Tables A-16 and A-17 present the details on the costs for particulate collection for facilities with from 7 to 100 ton/day capacity. All facilities with particulate control are assumed to have a heat recovery system. The heat recovery system reduces the flue gas temperature to around 500°F, which is a

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[a]The average steam value at Navy installations is slightly more than $\$4/10^6$ Btu. This figure includes all costs associated with steam production. The value of the steam from an incineration operation may only be equivalent to the fuel component of the $\$4/10^6$ Btu figure, which is probably $\$2$-$\$3/10^6$ Btu. The current labor and capital charge components may be fixed costs that would not change unless the total steam demand is met by the new incinerator installation.

Table A-12

COMPARISON OF ANNUAL OPERATING COSTS
FOR HYPOTHETICAL REFUSE INCINERATION SYSTEMS
(20 Ton/Day Design Capacity, 4140 Ton/Year Processed)

	No Heat Recovery/No Particulate Collection		Heat Recovery/No Particulate Collection	
	A 1 Shift Operation 5 day/week	B 2 Shift Operation 5 day/week	C 1 Shift Operation 5 day/week	D 2 Shift Operation 5 day/week
Operating Costs				
Materials, Supplies and Services				
Maintenance Supplies	9,625	7,000	13,750	8,125
Ash Disposal (4140 t/yr x 0.1117 x $10.75/t)	4,968	4,968	4,968	4,968
Subtotals	14,593(10%)	11,968(7%)	18,718(11%)	13,093(8%)
Labor				
Operation (2 men/shift at $6/hr)	27,955	55,910	27,955	55,910
Supervision (20% of operating labor)	5,591	11,182	5,591	11,182
Maintenance labor (2.5% of Investment)	9,625	7,000	13,750	8,125
Administration and support labor‡	11,000	11,000	12,250	12,250
Payroll burden (30% of labor)	15,542	26,673	17,864	26,240
Subtotals	69,713(50%)	111,765(68%)	77,410(46%)	113,707(65%)
Purchased Fuel and Utilities				
Fuel (4140 t/yr x 0.5 x 10^6 Btu/t x $2.50/$10^6$ Btu)	5,175	5,175	5,175	5,175
Electric power	1,242	1,242	2,484	2,484
Subtotals	6,417(5%)	6,417(4%)	7,659(4%)	7,659(4%)
Total Direct Charges	90,723(65%)	130,150*(79%)	103,787*(61%)	134,459*(77%)
Capital Charges†	48,559(35%)	29,169 (21%)	66,445(39%)	39,263(23%)
Total Annual Cost	139,282	159,319	170,232	173,722
($/ton refuse)	(~34)	(~38)	(~41)*	(~42)*
Present value	1,264,263	1,446,139	1,545,196	1,576,875

*No credit for sale of steam included.

†Calculated using a capital recovery factor with n = 25 year and i = 10%. (See Table A-9)

‡Assumed to be the same for cases A and B and the same for cases C and D.

Table A-13

ENERGY RECOVERY POTENTIAL
(≤ 20 Ton/Day Design Capacity)

Plant Design Capacity (ton/day)	Operating Schedule* (shift/day)	Steam Generation Rate** (lb/hr)	Steam Generation Rate** (lb/yr)	lb steam/ton refuse burned
20	1†	8670†	13.96×10^6 †	3372
20	2‡	5000‡	17.25×10^6 ‡	4167
7	1Δ	3030Δ	4.88×10^6 Δ	3370

*5 day/week operation, 90% of design capacity.

**At 50% thermal efficiency with a refuse heat content of 10.1 million Btu/ton and an auxiliary fuel use of 0.5 million Btu/ton.

†Assumes 1 hour required to remove ash and get up to temperature, 7 hours of steam generation, 4 hours of burndown on automatic control at end of 8 hour shift.

$$\left(\frac{20 \text{ tons} \times 0.9}{7 \text{ hours loading}}\right)\left(\frac{10.6 \times 10^6 \text{ Btu}}{\text{Ton}}\right)\left(\frac{7 \text{ hours steam generation}}{11 \text{ hours burning}}\right)(0.5)$$

= 8.67 million Btu/hr

≈ 8670 lb steam/hr

for 7 hour/day, 230 day/year

‡Assumes 1 hour required to remove ash and get up to temperature, 15 hours of steam generation, 4 hours of burndown on automatic control at end of second 8 hour shift.

$$\left(\frac{20 \text{ tons} \times 0.9}{15 \text{ hours loading}}\right)\left(\frac{10.6 \times 10^6 \text{ Btu}}{\text{Ton}}\right)\left(\frac{15 \text{ hours steam generation}}{19 \text{ hours burning}}\right)(0.5)$$

= 5.02 million Btu/hr

≈ 5000 lb steam/hr

for 15 hour/day, 230 day/year

ΔAssumes 1 hour required to remove ash and get up to temperature, 7 hours of steam generation, 4 hours of burndown on automatic control at end of 8 hour shift.

$$\left(\frac{7 \text{ tons} \times 0.9}{7 \text{ hour loading}}\right)\left(\frac{10.6 \times 10^6 \text{ Btu}}{\text{Ton}}\right)\left(\frac{7 \text{ hours steam generation}}{11 \text{ hours burning}}\right)(0.5)$$

= 3.03 million Btu/hr

≈ 3030 lbs steam/hr

for 7 hours/day, 230 day/year

Table A-14

COMPARISON OF ANNUAL OPERATING COSTS FOR HYPOTHETICAL REFUSE INCINERATION SYSTEM
(7.0 Ton/Day Design Capacity,* 1449 Ton/Year Burned)

	No Heat Recovery	Heat Recovery
Operating Costs		
Materials, Supplies, and Services		
Maintenance supplies	4,750	6,750
Ash Disposal (1449 ton/yr x 0.1117 x $10.75/t)	1,740	1,740
Subtotal	6,490(7%)	8,490(8%)
Labor		
Operation (2 men/shift at $6/hr)	27,955	27,955
Supervision (20% of operating labor)	5,591	5,591
Maintenance labor (2.5% of investment)	4,750	6,750
Administrative and support labor	7,850	7,850
Payroll burden	13,843	14,444
Subtotal	59,989(65%)	62,590(59%)
Purchased Fuel and Utilities		
Fuel (1449 ton/yr x 0.5 x 10^6 Btu/t x $2.5/$10^6$ Btu)	1,811	1,811
Electric Power	435	870
Subtotal	2,246(2%)	2,681(3%)
Total Direct Charges	68,725(74%)	73,761(70%)
Capital Charges	23,964(26%)	32,778(30%)
Total Annual Costs	$ 92,689	106,539**
($/ton refuse)	(~ 64)	(~ 74)**
Present Value	$841,338	$967,055

*1 shift operation, 5 day/week.

**No credit for sale of steam included.

-Calculated using a capital recovery factor with n = 25 years and i = 10%.

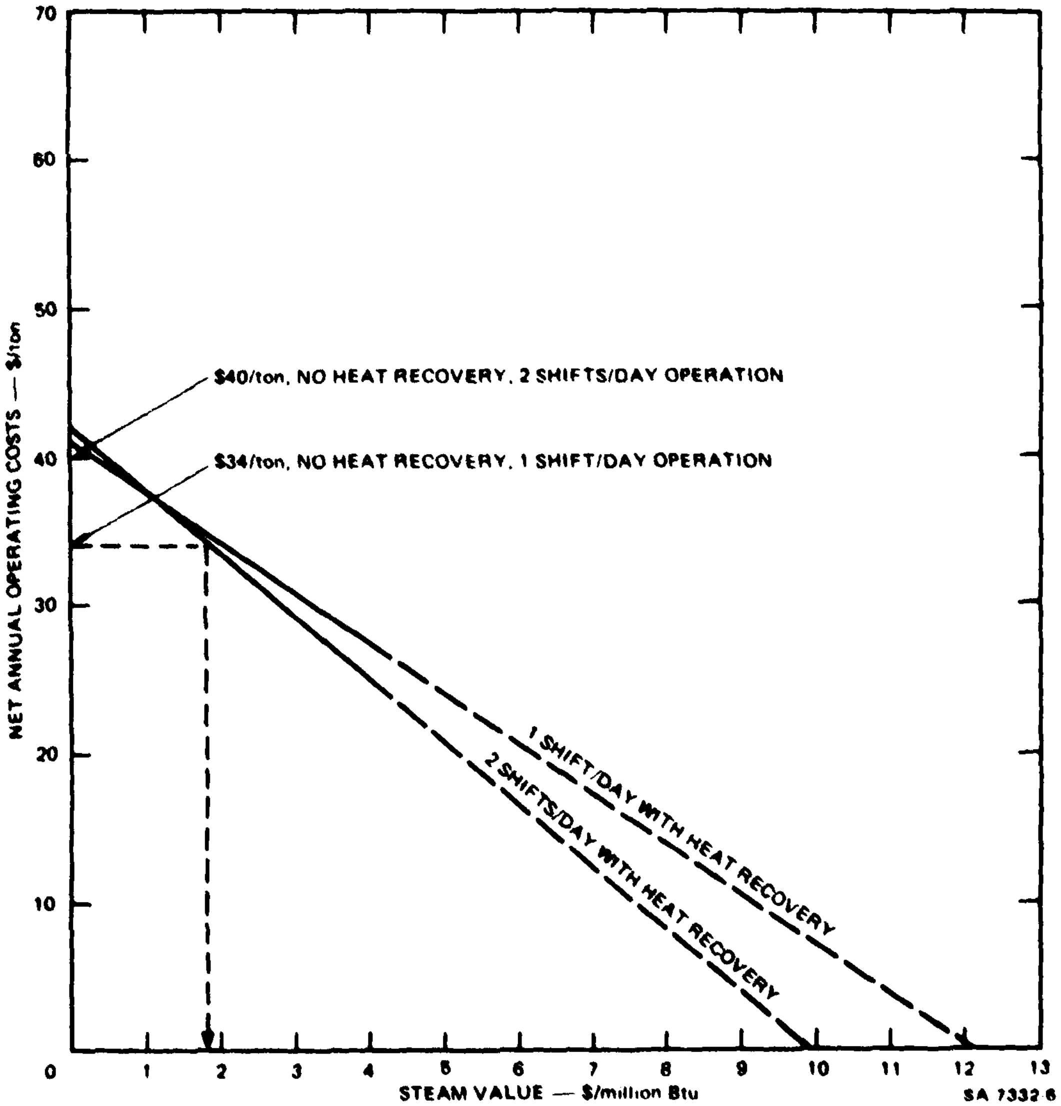

FIGURE A-4 NET ANNUAL OPERATING COSTS AS A FUNCTION OF THE VALUE OF STEAM (20 ton/day design capacity)

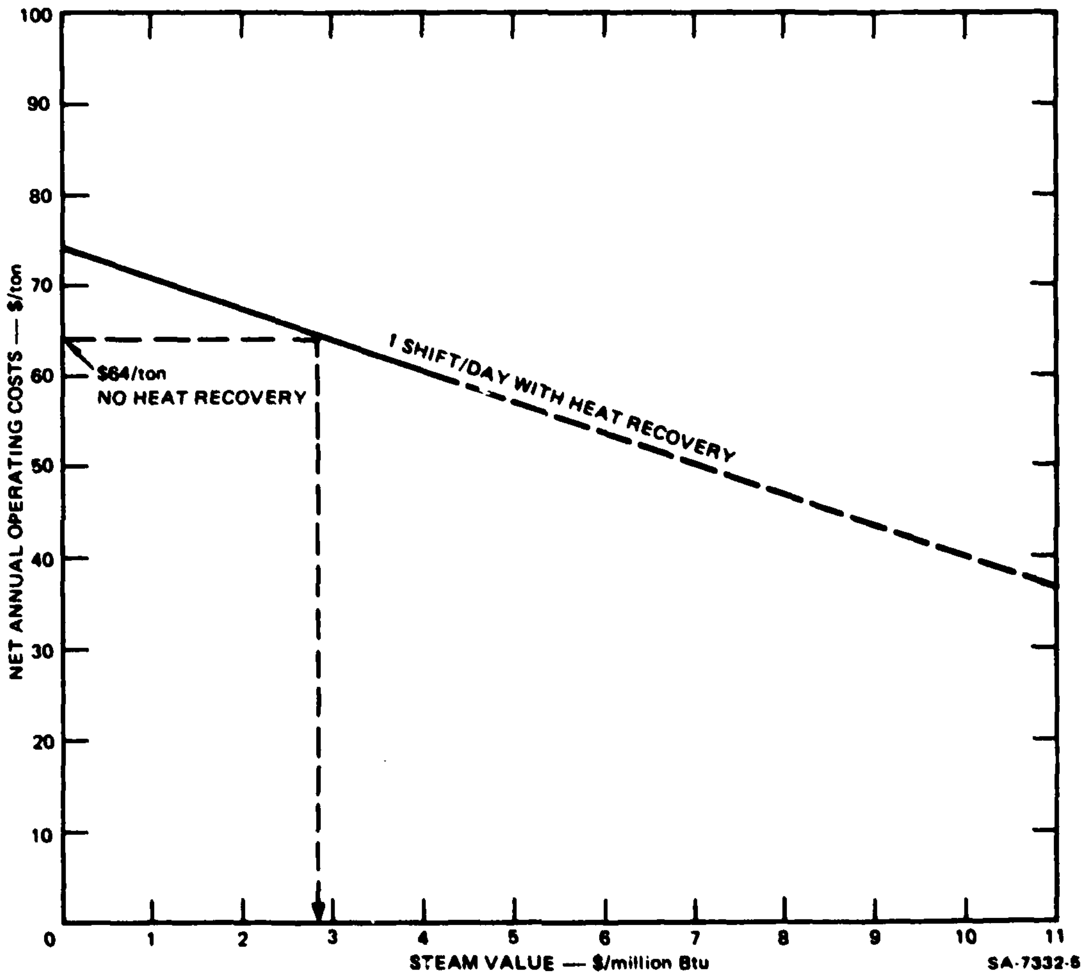

FIGURE A-6 NET ANNUAL OPERATING COSTS AS A FUNCTION OF THE VALUE OF STEAM (7 ton/day design capacity)

Table A-15

COMPARISON OF ANNUAL OPERATING COSTS FOR HYPOTHETICAL REFUSE INCINERATION SYSTEMS (50 AND 100 TON/DAY DESIGN CAPACITIES)

	50 Ton/D Installed Capacity (with heat recovery)		100 Ton/D Installed Capacity (with heat recovery)	
	Without Particulate Control	With Particulate Control	Without Particulate Control	With Particulate Control
Operating Costs				
Materials, Supplies and Services				
Maintenance supplies (2.5% of investment)	24,125	34,025‡	36,250	56,250‡
Ash disposal ($10.75/dry ton)	12,428	12,428	24,856	24,856
Subtotal	36,553(10%)	46,453(11%)	61,106(13%)	81,106(14%)
Labor				
Operators (2 men/shift @ $6/hr)	83,866	83,866	83,866	83,866
Supervision (20% of operating labor)	16,773	16,773	16,773	16,773
Maintenance (2.5% of investment)	24,125	34,025‡	36,250	56,250‡
Administration and support labor	24,953	24,953	27,377	27,377
Payroll burden (30% of direct labor)	44,717	47,687	49,280	55,280
Subtotal	194,632(53%)	207,304(52%)	213,546(44%)	239,546(43%)
Purchased Fuel and Utilities				
Fuel ($2.50/$10^6$ Btu)	12,938	12,938	25,875	25,875
Power ($0.03/kWh)	6,210	9,310	12,420	18,620
Subtotal	19,148(5%)	22,248(6%)	38,295(7%)	44,495(8%)
Total Direct Charges	250,333(68%)*	276,005(69%)*	312,947(64%)*	365,147(65%)*
Capital Charges	115,523(32%)	126,423(31%)	173,736(36%)	195,736(35%)
Total Annual Cost	365,856	402,428	486,683	560,883
($/ton refuse)	(35.25)	(29.0)	(23.50)	(27.0)

*No credit for steam.

†Calculated using a capital recovery factor with n = 25 years and i = 10%.

‡Maintenance for baghouse calculated as; materials 10% and labor 10% of investment.

Table A-16

PARTICULATE CONTROL SYSTEM DESIGN CAPACITIES AND INVESTMENT COSTS

Quantity of Refuse Generated* (ton/day)	Plant Design Capacity** (ton/day)	Quantity of Refuse Burned*** (ton/day)	(ton/year)	Number of Shifts Plant Operated per Day	Hours of Fabric Filter Operation (per day)	(per year)	Flue Gas Design Flow† (acf/min) (at 1625°F)	(at 500°F)	Installed Cost of Fabric Filtration System‡ Total Investment	($/acfm)	Power Requirements§ (kWh/year)
~ 6	7	6.3	1,449	1	11.5	2,645	~ 13,000	~ 6,000	$ 54,000	~ 9.0	11,834
~ 17	20	18	4,140	2	19.5	4,485	~ 21,000	~ 10,000	77,500	~ 7.8	43,478
~ 42	50	45	10,350	3	24	5,520	~ 37,000	~ 17,000	99,000	~ 5.8	90,560
~ 85	100	90	20,700	3	24	5,520	~ 74,000	~ 34,000	200,000	~ 5.8	181,116

*Quantity generated 260 day/year.

**Plant operates at 90% of design capacity.

***Quantity burned 230 day/year.

†Calculated based on 1.4 times average flow for one and two shift operation and 1.2 times the average flow for the three shift operation.

‡Designed to operate at ≤ 500°F with glass fiber filter.

§Equivalent to 8-10 kWh/ton refuse processed based on a pressure drop of 4 inches water.

Table A-17

ANNUAL OPERATING COSTS FOR PARTICULATE CONTROL SYSTEMS

	PLANT DESIGN CAPACITY			
	7 t/d (1449 t/y)*	20 t/d (4140 t/y)*	50 t/d (10,350 t/y)*	100 t/d (20,700 t/y)*
Operating Costs				
Materials and Supplies				
Maintenance supplies (10% of investment)	5,400	7,750	9,900	20,000
Subtotals	5,400	7,750	9,900	20,000
Labor				
Maintenance labor (10% of investment)	5,400	7,750	9,900	20,000
Payroll burden	1,620	2,325	2,970	6,000
Subtotals	7,020	10,075	12,870	26,000
Purchased Utilities				
Electric power (~ 10 kWh/t)	435	1,240	3,100	6,200
Subtotals	435	1,240	3,100	6,200
Total Direct Charges	\$12,855	\$19,065	\$25,870	\$52,200
Capital Charges†	5,950	8,540	10,900	22,000
Total Annual Cost	\$18,805	27,605	36,770	74,200
(\$/ton refuse)	(~ 13)	(~ 6.7)	(~ 3.6)	(~ 3.6)
Present Value	\$170,693	\$250,570	\$333,761	\$673,513

*Actual tons burned per year

†Calculated using a capital recovery factor with n = 25 years and i = 10%.

tolerable temperature for the fabric filter.[a] Filter material will have to be chosen to resist burning carbon particles that may be emitted from the secondary combustion chamber.

Table A-18 shows the estimated quantities of steam to be generated by the 50- and 100-ton/day facilities. Figure A-6 illustrates how the net annual operating costs are affected by the value of the steam.

F. Comparison of Investment and Operating Costs for Small and Large Facilities

In discussions of resource recovery facilities, the investment costs are commonly examined in terms of dollars per ton of daily capacity as a function of the plant capacity. One such comparison for large capacity systems (greater than 400 ton/day) is shown in Figure A-7. Depending on the size and types of process employed, an energy production operation may require an investment of from $30,000 to well in excess of $50,000 per ton of daily capacity. These facilities are all especially designed field-erected units.

Figure A-8 has been prepared on the basis of data presented in this study. The investment costs per ton of daily capacity are far below the figures previously mentioned, primarily because of shop fabrication of equipment, no preprocessing, and low-pressure steam production. If one were to consider addition of a shredding operation at the 100-ton/day plant operating one shift per day,[b] the incremental investment

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[a]400-450°F may be a safer temperature range to ensure acceptable fabric life.

[b]Shredders for MSW are limited to a certain minimum size because of feed opening requirements. Units are not generally supplied with capacities below 15 to 20 tons/hr.

Table A-18

ENERGY RECOVERY POTENTIAL
(50- and 100-ton/day Design Capacities)

Plant Design Capacity (tons/day)	Operating Schedule[a] (shifts/day)	Steam Generation Rate[b] (lb/hr)	(lb/yr)	Lb Steam/Ton Refuse Burned
50	3	9,940[c]	54.87×10^6	5,300
100	3	19,880[d]	109.74×10^6	5,300

---

[a]5 days/week at 90% of design capacity.

[b]At 50% thermal efficiency with a refuse heat content of 10.1×10^6 Btu/ton and an auxiliary fuel use of 0.5 10^6 Btu/ton.

c

$$\frac{50 \text{ tons} \times 0.9}{24 \text{ hours}} \times \frac{10.6 \times 10^6 \text{ Btu}}{\text{ton}} \times 0.5 = 9.94 \times 10^6 \text{ Btu/hr}$$

(Approximately 9,940 lb steam/hr for 24 hr/day, 230 day/yr)

d

$$\frac{100 \text{ tons}}{50 \text{ tons}} \times 9.94 \times 10^6 \text{ Btu/hr} = 19.88 \times 10^6 \text{ Btu/hr}$$

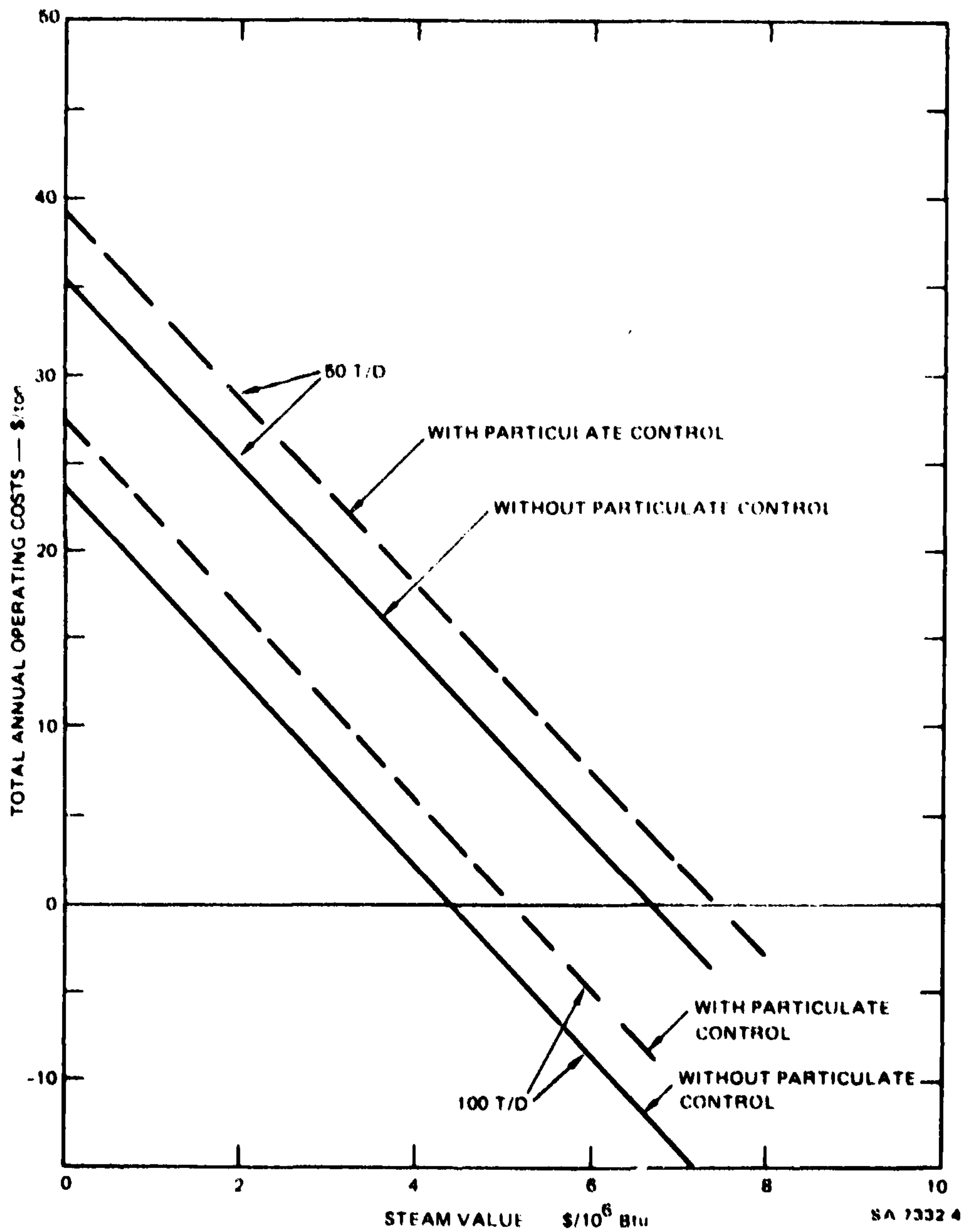
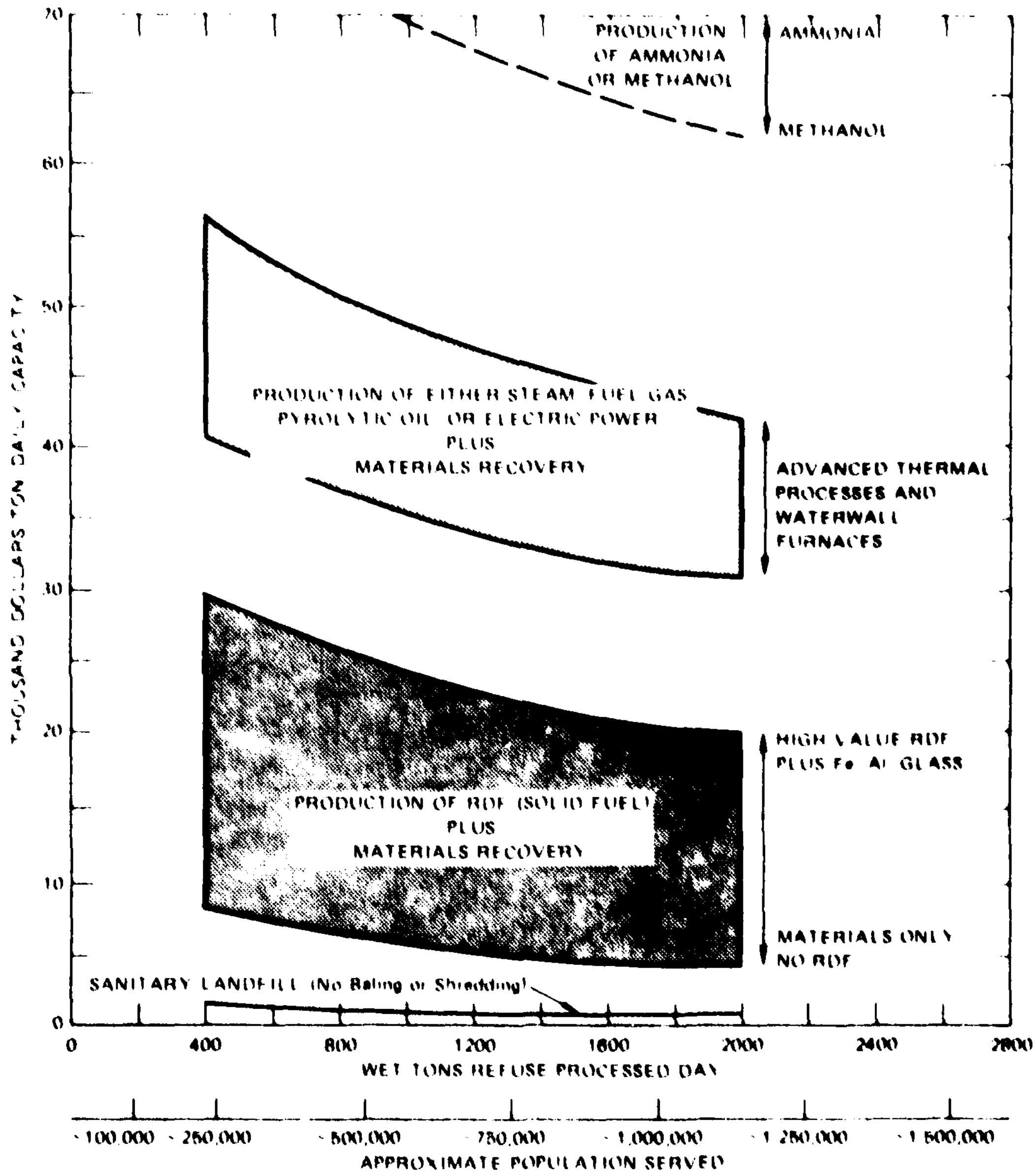


FIGURE A-6 NET ANNUAL OPERATING COST AS A FUNCTION OF STEAM VALUE (50 and 100 ton/day design capacities)



NOTE: Mid 1978 costs
SOURCE: SRI International

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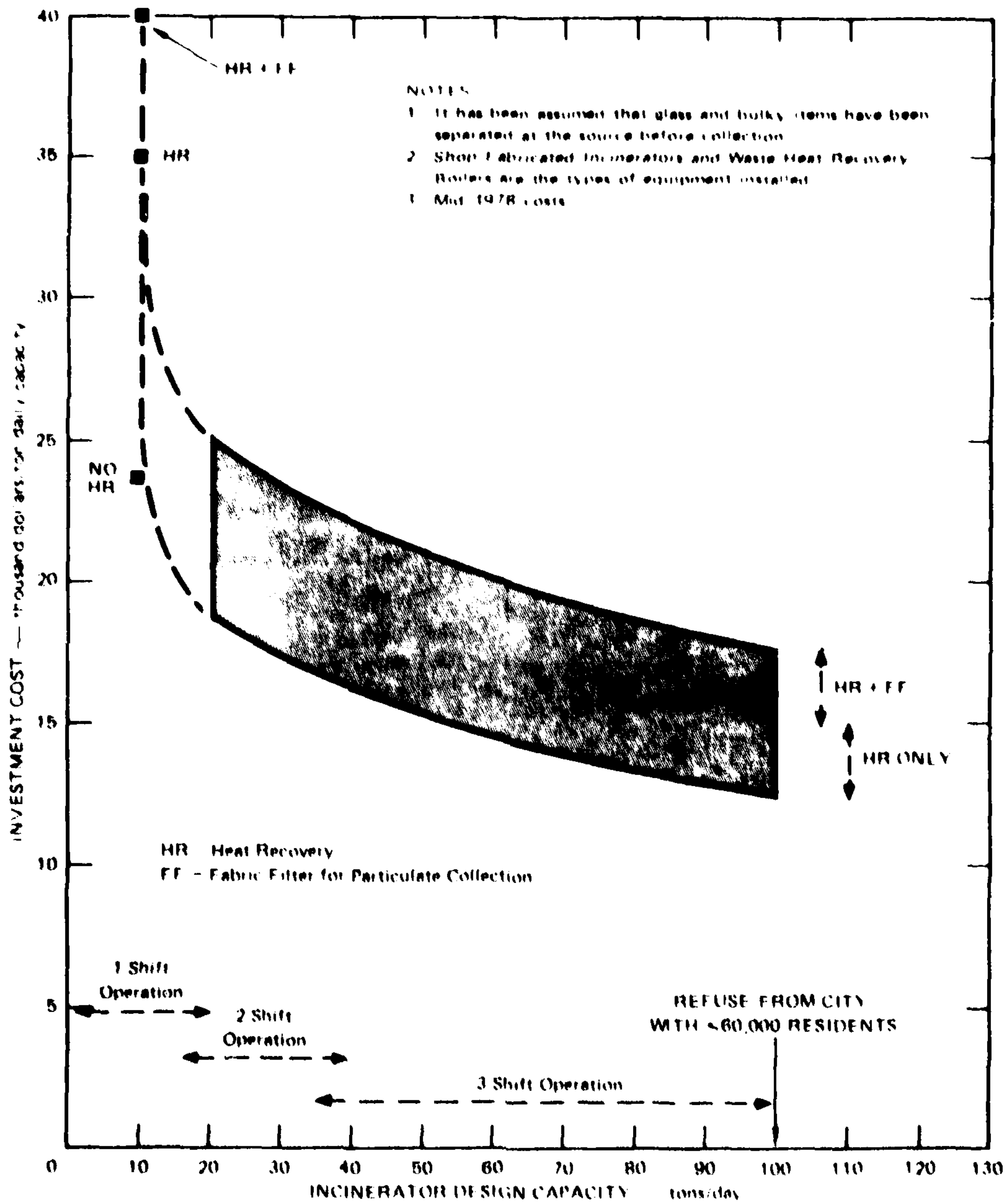
FIGURE A-7 APPROXIMATION OF RELATIVE INVESTMENT REQUIREMENTS BASED ON ACTUAL AND ESTIMATED COSTS FOR LARGE REFUSE PROCESSING FACILITIES



SOURCE SRI International

SA 7332.3

FIGURE A-8 APPROXIMATION OF INVESTMENT REQUIREMENTS FOR SMALL REFUSE INCINERATION FACILITIES WITH HEAT RECOVERY

might exceed $5,000/ton of daily capacity, or more than 30% of the incineration plant investment without shredding. Adding such operations as aluminum recovery would further increase the investment.

On the basis of differences in investment cost per ton of daily capacity, operating costs for the small facilities might be expected to be lower than those for large facilities; they are actually higher, however, primarily because of labor cost. Increasing the plant size by a factor of 20, from 50 to 1,000 ton/day, probably increases the work force by four to five-fold. There is a tremendous savings, therefore, in labor costs per ton of refuse processed for a large plant relative to a small plant. Estimated total labor costs at the 50-ton/day plant are about $20/ton of refuse processed. For a 1,000-ton/day plant, the total cost should be less than $6/ton.[a] For 50- to 100-ton/day plants, estimated annual labor costs are about constant,[b] so that for a 100-ton/day facility, the total labor costs would be $\geq$ $10/ton of refuse processed.

Because of the complexity of some processes being developed for very large systems, however, the net costs of operating the facilities are not projected to be low. To provide some perspective concerning estimated net annual operating costs per ton for large facilities using pyrolysis processes, Table A-19 from a study prepared by Bechtel Corporation is shown. The processes considered included the Andco Torrax process, the Union Carbide Purox process, and the Occidental flash pyrolysis process. The costs must be considered preliminary estimates because none of these processes has been commercially demonstrated. To provide

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[a]The assumption for the plants ranging in capacity from 50-100 ton/day was that two operators are required per shift.

[b]Based on data from the Edison Coordinated Joint Regional Solid Waste Energy Recovery Project conducted by Bechtel (April 1977). Data are for an Andco Torrax facility with a capacity to process 1,000 ton/day of MSW.

Table A-19

ESTIMATED INVESTMENT AND NET OPERATING COSTS FOR LARGE PYROLYSIS SYSTEMS

Net System Cost for Primary Sites as of the First Year of Operation
($/ton solid waste)

System Capacity (tons/day)	Site	Pyrolysis System: Andco	Union Carbide	Occidental
500	Santa Barbara County Juvenile Hall	30.97	-	-
	Los Angeles County - Long Beach			
1,000	Spring/California	16.85	22.59	18.83
1,000	Spring/California (PUROX-electricity)	-	25.91	-
	Ventura County			
1,000	Mandalay	16.74	18.67	18.83
1,500	Mandalay:			
	Ventura Cost	15.41	13.82	14.34
	Santa Barbara Cost	22.08	20.60	21.01

Estimated Capital Costs Escalated to the Midpoint of Construction
($ thousands)

System Capacity (tons/day)	Site	Pyrolysis System: Andco	Union Carbide	Occidental
500	Santa Barbara County Juvenile Hall	$38,471	-	-
	Los Angeles County -			
1,000	Spring/California	$51,330	$71,405	$49,374
1,000	Spring/California (PUROX-electricity)	-	$64,479	-
	Ventura County			
1,000	Mandalay	$51,134	$61,332	$50,007
1,500	Mandalay	$74,523	$82,468	$65,978

Source: Edison-Coordinated Joint Regional Solid Waste Energy Recovery Project Feasibility Investigation, report prepared by Bechtel (April 1977).

demonstrated. To provide some perspective on the costs for a proven process such as a Von Roll water-wall incineration facility (producing steam), the Saugas, Massachusetts, facility requires a tipping fee of approximately $15/ton of refuse. It appears unlikely that the Navy will be able to send refuse to large resource recovery facilities located near Navy operations for much less than a tipping fee of $10/ton. In many cases, the fee will be considerably higher than this, and a significant hauling fee may also be required to transport the refuse to the facility.

G. Summary of Findings

Figures A-9 and A-10 summarize the results of the economic analysis. The net annual operating costs are plotted as a function of plant design capacity and steam value. Figure A-9 presents costs for facilities without fabric filters for particulate control and Figure A-10 illustrates costs for facilities with fabric filters.

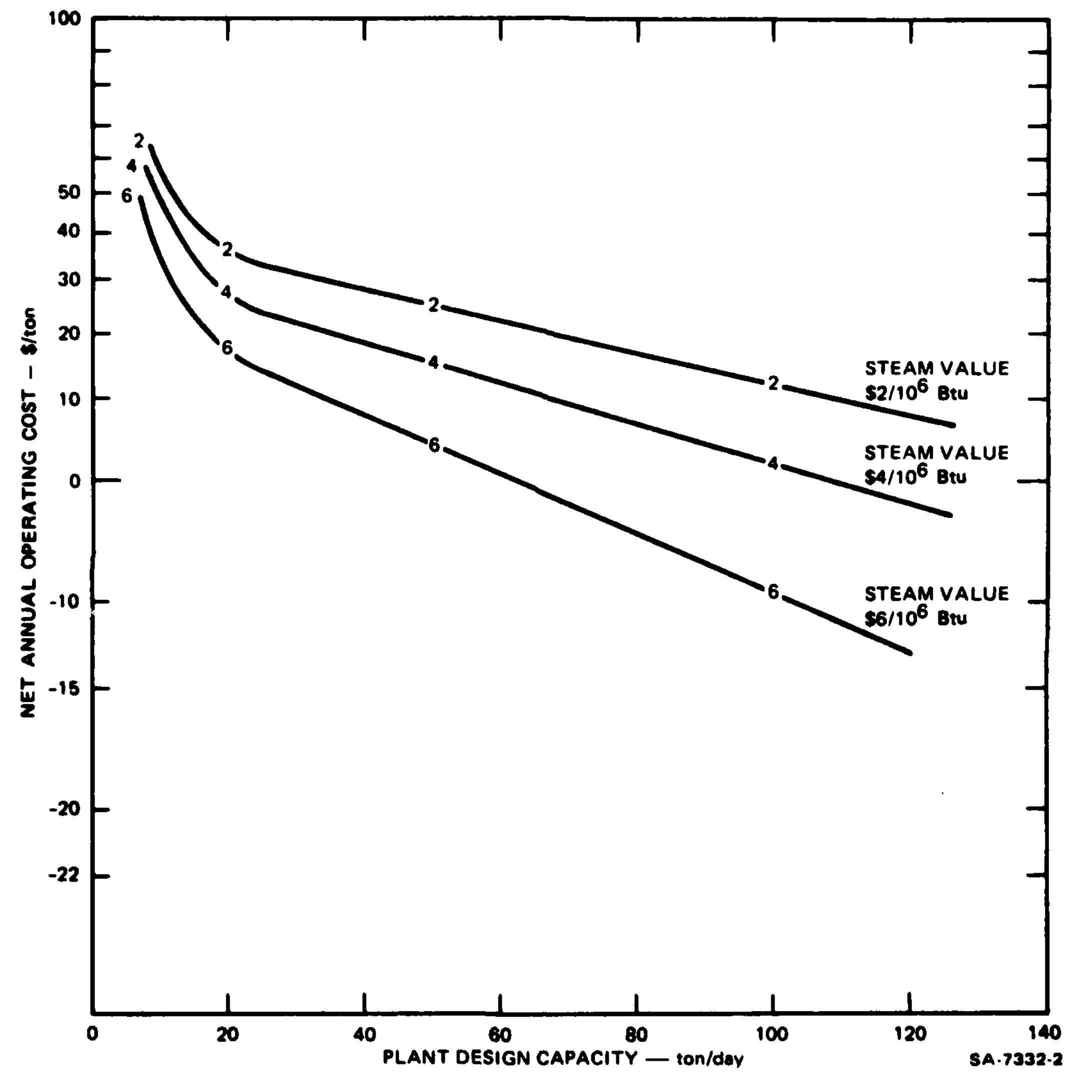

FIGURE A-9 NET ANNUAL OPERATING COST AS A FUNCTION OF PLANT DESIGN CAPACITY WITH NO PARTICULATE COLLECTION

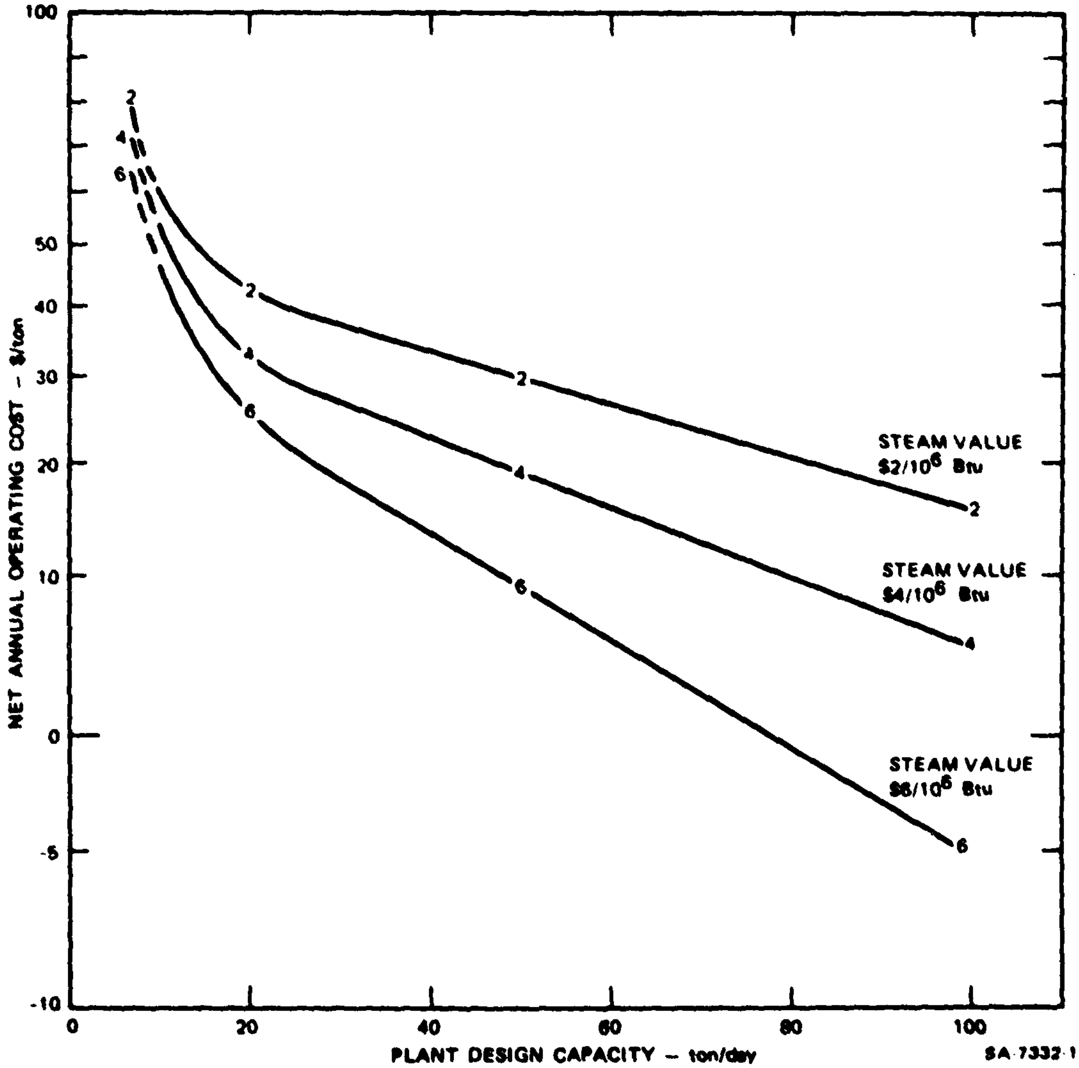

FIGURE A-10 NET ANNUAL OPERATING COST AS A FUNCTION OF PLANT DESIGN CAPACITY WITH PARTICULATE COLLECTION

V FUTURE RESEARCH NEEDS

On the basis of the findings of this study of shop-fabricated incinerators, we have identified the following topics as possible subjects for further research and evaluation by the Navy (possibly in cooperation with DOE and EPA):

(1) A preliminary technoeconomic evaluation of the O'Connor combustor, including a site visit to the 50-ton/day plant in Yokohama, Japan.

(2) A preliminary technoeconomic evaluation of a fluidized bed combustor (preceded only by a trommel) for solid waste combustion at Navy installations with more than 50 ton/day of solid waste.

(3) A study of the operating characteristics, performance, investment, and operating costs for particulate control devices for small capacity solid waste combustion units (20 to 200 ton/day).

(4) A study of the costs for controlling nuisance odor problems at resource recovery plants by means of scrubbing building ventilation system exhaust.

(5) A study of possible design improvements for shop-fabricated incinerators to achieve more complete combustion of fixed carbon in ash and to achieve better process control.

(6) A continuing review and evaluation of developments in small-scale solid waste conversion units, with written reports prepared annually on significant design improvement. (Auger bed incinerator development is a possible subject to be included, as well as updates on gasification and pyrolysis units. Identification of developments in Europe with mechanical grate units is another possible topic.)

(7) A review of Navy solid waste components that if combusted could result in the emission of significant quantities of non-criteria air pollutants.